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PERFORMANCE OF A VARIABLE CONDUCTANCE
HEAT PIPE HEAT EXCHANGER

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The primary objective of the work is to evaluate the performance of an air to air variable conductance heat pipe heat exchanger (VCHPHX). This type of heat exchanger is of particular interest to the commercial aircraft industry because of its unique control system. The results from this research will help to provide the engineer with experimental data necessary to design a full scale prototype heat exchanger to be tested insitu.

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This report has been reviewed by the EOARD Information Office and is releasable to the National Technical Information Service (NTIS). At NTIS it will be releasable to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

CARY A. FISHER
Colonel, USAF
Chief Scientist

JERRY R. BETTIS
Lt Colonel, USAF
Deputy Commander

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1. INTRODUCTION

1.1 Background

The work begun in 1980-81 by Steve Drouilhet is currently being extended by the writer.[1] The primary objective of the work is to evaluate the performance of an air to air variable conductance heat pipe heat exchanger (VCHPHX). This type of heat exchanger is of particular interest to the commercial aircraft industry because of its unique control system. The results from this research will help to provide the engineer with experimental data necessary to design a full scale prototype heat exchanger to be tested insitu.

1.2 Scope of Work

Two heat exchangers of the type mentioned above have been supplied by the contractor. The heat exchangers are to be mounted in a test stand and instrumented for performance analysis. These tests should document not only the absolute performance in terms of effectiveness, but they should also be sufficient toevaluate the dependant variables in both a qualitative and a quantitative way. At present, little is known about the VCHPHX. Because of this, the question of why something happens often arises during the analysis. Answering this question may be the most important contribution of this work. Explanations which can be made using conventional heat pipe theory or a modified version of it will be provided with the hope of future usefulness to the engineer.

2. THE VARIABLE CONDUCTANCE HEAT EXCHANGER

The prototype heat exchanger which is the subject of this work is an air to air heat exchanger. The novelty of the design isthat heat transfer is not the typical stream to stream heat transfer across a plate or a tube wall. Instead, heat is transferred to a finned evaporator and from a finned condenser via a heat pipe. A simple arrangement for this type of heat exchanger is shown in figure 1. The variable conductance heat pipe is to the condenser fins a heat source and to the evaporator fins a heat sink. Since heat transferred from the evaporator to the condenser must be conducted via the heat pipe, a variable conductance heat pipe means a variable conductance heat exchanger. This is the principal advantage of the variable conductance heat pipe heat exchanger, the ability to modulate power transfer independant of stream inlet conditions. The two types of heat exchangers may be modelized using the electrical circuit analogy as shown in figure 2. Note that for the conventional heat exchanger the various resistances are essentially fixed, preventing current (heat flow) modulation for a fixed voltage (temperature difference). However, the VCHPHX analog has one variable resistance, that of the heat pipe; consequently, power modulation is possible for a fixed voltage.

The VCHPHX relies on mainly two technologies; finned tube heat exchanger technology and variable conductance heat pipe technology. While the former is well understood and characterized from years of use, the latter is relatively new. Indeed the VCHP based on liquid reservoir temperature control is at this stage purely experimental.

While the principal ofjective of this work is performance evaluation, the opportunity to add to what is known about the VCHP is obvious. The data gathered for performance analysis is useful for exploring VCHP operation as will be shown later in Chapter 6.

3. EXPERIMENTAL FACILITY

3.1 The Test Stand

The prototype heat exchanger is mounted in a stand which furnishes 2 streams of air at varying temperatures and mass flow rates. Figures 3A and 3B illustrate the arrangement of the components. Power from the heated evaporator stream is transferred to the cooler condenser stream. The power transferred is varyable, depending on the inlet stream conditions and the reservoir temperatures. The stream inlet conditions may be varied as follows:

Condenser

Temperature	29-35	C
Mass Flow Rate	0-.1	KG/sec

Evaporator

Temperature	45-150	C
Mass Flow Rate	0-.1	KG/sec

The reservoir temperature may be adjusted within the following range:

Reservoir

Temperature	16.7-90	C

3.2 The VCHPHX

The heat exchanger consists of 16 vertical heat pipes arranged into 4 rows of 4 heat pipes each. The condenser region and the evaporator region of the heat exchanger is fitted with aluminum fins to provide an extended surface for heat transfer. Each row of 4 heat pipes is gathered to a common liquid reservoir. There are 4 reservoirs. Each of the liquid reservoirs is fitted with a Peltier cell to either heat or cool the liquid within the reservoir. A simple aluminum channel with aluminum honeycomb within serves as either heat sink or heat source for the Peltier cells. The condenser air stream is induced through the channel. Refer to figures 4 and 5 for details.

Heat exchanger dimensions are given in Appendix B. Properties of the heat pipe working fluid are also included in this appendix.

3.3 Measurements and Consequent Instrumentation

Evaluating the performance of the heat exchanger system is a task which requires the information gained from a first law analysis of the system. The system may be divided into the following 4 sysbystems:

1. Condenser
2. Evaporator
3. Reservoirs
4. Peltier Cooler

Evaluating these individual sybsystem performances requires a first law energy balance for each. The measurements taken by the writer provide sufficient data to make a first law analysis of the system as a whole; direct measurement of the subsystem performances is not practical and so these performances are obtained indirectly when required.

The measurements recorded to obtain a first law analysis on the system are listed in Table 1 below. An annotated sketch of the system with state points is also provided, figure 6. It is now possible to write the first law energy balance for the entire system:

$$P_{cond} + P_{evap} + P_{cooler} + P_{elect} + P_{convection} = 0 \qquad (1)$$

Note that a fifth term appears in equation (1) above which is not obtained by direct measurement.

Table 1 List of Measurements

State Point	Measurement	Transducer
1	Temperature	Single T/C
2	"	15 T/C Grid
3	"	Single T/C
4	"	15 T/C Grid
5	"	Single T/C
6	"	Single T/C
7	Pressure	Setra Tdx. (350 mm)
8	"	Setra Tdx. (350 mm)
9	Elect. Power	Voltmeter/Ampmeter

Note this term, $P_{convection}$, is the power exchange between the system and the surroundings due to convection.

In addition to the measurements listed thus far, several additional measurements were taken in order to relate the system performance to the operating conditions. These are given in table 2 below.

Table 2 Parametric Measurements

Measurement	Transducer
Reservoir Temperature	
Row 1	Single T/C
Row 2	" "
Row 3	" "
Row 4	" "
Ambient Temperature	" "

Having described the various measurements which were recorded, the instrumentation will now be detailed. Please see figures 7 and 8. The two fundamental quantities measured are temperature and pressure. The measurement chains for each are

deficted in figures 7 and 8. A typical first law analysis is made by the computer once the heat exchanger system has reached steady state. The sequence of operations, transducer scan/ calculations/printout, is completed in about 90 seconds. Appendix A contains a listing of the BASIC program which was written to accomplish the data acquisition and to perform the first law calculations. A sample printout is also included in this appendix.

4 TESTING PROCEDURE

Since the primary emphasis of this work is to evaluate heat exchanger performances, the testing program must document the behavior of the heat exchanger over a wide range of operating conditions. While one might propose a large number of tests (ie. operating conditions), it is clear that limiting cases will be of upmost importance. Once these limits are established, the work of filling in the "holes" in the data can be carried out in a logical way.

Remembering that two VCHPHX are to be tested, the difference between the two is now discussed. The first configuration is as shown thus far, with the reservoirs located at the bottom. The second configuration has reservoirs located at the top. The reason for this design variation is easily understood. Reservoirs located at the bottom are physically nearest the hot evaporator; this configuration favors the case of heated reservoirs. Reservoirs located at the top favors the case of cooled reservoirs. In each case, heat flows via conduction in the heat pipe wall to either help or to hinder the reservoir temperature control system. From this point on the writer will refer to the two configurations as the L prototype for lower reservoirs and the U prototype for upper reservoirs.

The parameters which may be varied during the tests are:

MR   Mass Ratio   ($\dot{m}_c / \dot{m}_e$)

MRT   Mean Reservoir Temperature   (C)

T_{ei} Temperature at the evaporator inlet   (C)

T_{ci} Temperature at the condenser inlet   (C)

Since documenting the limiting cases is the first goal for the
performance tests, the writers idea of a limiting case is defined:

> A limiting mode of operation has been reached when the
> effects of the control system cease to modify the
> behavior of the heat exchanger.

A limiting case is thus a loss of controlability. This loss of
control will be reached at either extreme of heat exchanger op-
eration. Operating points exist at which for given air inlet
cpmditions, a maximum power transfer is achieved and at which
a minimum power transfer is achieved. The range between these
two operating points constitutes the range of controlability.
There is, however, a catch to this line of reasoning. Note that
the limits of controlability depend on the air inlet conditions
and perhaps the mass flow ratio. Bearing this in mind, a salient
point comes to light. Understanding the reasons for the existance
of the limits can lead to better heat exchanger design and
therefore they should be evaluated. With this information the
experimenter can provide the designer with an important tool,
that of prediction.

Determination of the limiting cases establishes the range
of testing possible. Data gathered over this interval must be
sufficient to describe the response of the heat exchanger when
the control parameters are varied. The following chapters will
propose reasons for controlability, so at the present the writer
admits only that modulation of the mentioned parameters does
control power transfer within limits. In the proposed application
the single control parameter will be the reservoir temperature.

Mass flow ratio and inlet temperatures will not in general be modulated.

For a given set of operating conditions,

MR   set

T_{ei} set

T_{ci} set,

power transfer from the evaporator to the condenser may be modulated by varying the mean reservoir temperature. Two approaches are considered:

1. Cool or heat each reservoir equally. This amounts to providing equal power to each Peltier cell.

2. Cool or heat each reservoir independantly.

The merits of each approach have been evaluated for the L prototype. Only the former approach has been evaluated for the U prototype.

5 TEST RESULTS

5.1 Control Via Variable Peltier Cell Power

Both the U and The L prototypes were tested using this mode of control. For a given set of stream inlet conditions, the range of controlability was determined. Operation within this band provided ample data to characterize a broad linear range of control for each of the heat exchangers.

Figures 9 and 10 depict the controlability of the L and U prototypes. The graphs were produced using the following method:

1. The heat exchanger was allowed to come to equilibrium for the given set of stream inlet conditions with no Peltier cell power (the reservoirs being well insulated from the surroundings)
2. This equilibrium, zero Peltier cell power, average reservoir temperature is plotted as a vertical line
3. The system was forced from equilibrium by providing Peltier cell power.

The abcissa can be thought of as a figure of merit. The units, degrees C per watt reflect the mean reservoir temperature change from 2) above per watt of control power. Since the power transferred from the evaporator to the condenser is a function of mean reservoir temperature, the larger the figure of merit, the better. Note the broad linear range of evaporator power versus mean reservoir temperature. This linear control range is a desirable feature from the standpoint of automated control. The condenser power curves for each heat exchanger exhibit different behaviors at the limits of controlability. The U prototype has clear asymptotic values at either extreme while the L prototype is essentially linear throughout the achievable range

of reservoir temperatures. For the Uprototype, operating points are reached after which increasing or decreasing mean reservoir temperature has no discernable effect. Clearly, limits have been reached which are unalterable by the control system. These limits must have arisen due to heat exchanger failure of some sort. The L prototype does not reach these limits for the stated operating conditions. One might argue why this occurs, but figure 11 points out an identical behavior to the U prototype at the upper limit. Note that the inlet stream conditions have been changed in order to obtain this graph. It was not possible to illustrate the lower asymptotic extreme for the L prototype, but its existance is well indicated.

5.2 Control By Selective Reservoir Heating

The U prototype heat exchanger performance was evaluated while selectively heating the reservoirs. If, for instance, reservoir 1 was heated, then reservoirs 2,3, and 4 were cooled. Peltier cell power was held constant at 12 watts total for the 4 cells. Figure 3 explains the reservoir numbering scheme while Table 3 contains the data from 9 of the possible 16 combinations.

From the data, it is clear that each of the 4 reservoirs has a unique effect on performance when heated. Heating reservoir 4 achieves the greatest evaporator power while heating reservoir 1 achieves the lowest. This can be explained by the placement of the reservoirs. Reservoir 4 communicates with the 4 heat pipes in row 4. This row of heat pipes is located at the evaporator inlet and is therefore exposed to the maximum stream temperature. Thus for a given Peltier cell power, row 4 has the potential to reach the highist temperature (the data comfirms this line of reasoning).

RESERVOIRS ACTIVE 1 2 3 4	QUANTITY OF INTREST	MASS FLOW RATIO			
		1.0	0.8	0.6	0.4
	Mean Reservoir Temp η_{cond} η_{evap} P_{evap}/P_{cond}	29 19 20 859/792	30 17 18 786/744	30 15 16 682/632	27 11 12 431/413
		30 21 23 979/898	39 19 20 880/829	29 17 18 712/698	29 14 15 590/542
		27 21 24 996/879	29 20 22 934/846	29 18 20 785/716	30 14 16 611/544
		30 24 26 1176/1048	30 21 23 992/874	29 18 20 837/725	30 14 16 632/553
		31 23 23 995/971	34 21 22 970/938	34 20 20 817/827	34 17 17 683/656
		35 27 29 1238/1144	37 26 28 1186/1097	38 23 24 1017/961	39 19 20 765/731
		35 29 32 1393/1254	34 25 28 1214/1092	34 21 24 974/864	35 16 19 745/641
		32 25 26 1123/1046	33 22 24 1014/952	34 20 21 901/829	
		32 24 27 1125/1026	33 22 24 989/916	33 19 21 850/775	33 15 16 634/580

TABLE 3   Data For Individually Heated Reservoirs

Increasing the reservoir temperature forces more working fluid to enter the heat pipe; an increase of the average thickness of the liquid profile within the wick results. Pumping losses within the liquid are reduced and more power is transferred.

Is this mode of control sufficient. The writer thinks not. While the heat exchanger does admit to control by selective reservoir heating, the discrimination is poor. Note that while the range of controlability is as good as for the alternate mode of control, the ability to provide smooth evaporator power modulation is lacking. Indeed, the maximum number of power increments is limited to 16. Were these 16 increments evenly distributed this mode of control might be feasable. Since they are not, the hope for control soley by resevoir selection is remote. This mode of control may, however, be important in order to augment the alternate mode.

5.3 Practical Considerations

The most outstanding difference between the two prototypes is the turn down ratio which the writer defines as follows:

TDR = Max Condenser Power/Min Condenser Power   (2)

From a practical standpoint, this quantity is very important; indeed, maximizing this ratio was the motivation behind testing both the L and the U prototypes. From figures 9 and 10, the U prototype has a TDR of about 10 while the L prototype has a TDR of about 3.

A second practical consideration is identified by the following ratio:

CPR = Condenser Power / Peltier Cell Power   (3)

This control power ratio (CPR) relates the "cost of control". Clearly, one would like to effect control with the smallest

possible control power. That is to say that the CPR should be maximized. Since the condenser power is controlled largely by the mean reservoir temperature, the plot of reservoir temperature versus Peltier cell power indicates the ease of control (see figures 12 and 13). Ideally both prototypes should have equal condenser powers for equal mean reservoir temperatures at a given set of operating conditions. This is not true in the present case; the reasons for this may include different quantities of working fluid in the pipes. Reference to figure 14 allows one to evaluate the cost of control for each of the prototypes. Noting the heated reservoir case, the CPR is noticeably better for the upper reservoir configuration. Indeed, the U prototype minimum condenser power is the equilibrium temperature; hence no U prototype curve is plotted for the case of cooled reservoirs. This point is a valuable one to note since a simplification of the control system results.

5.4 Transient Response

The transient response of both prototypes was evaluated by making a step change in Peltier power and then recording the following variables versus time:

1. Mean reservoir temperature
2. Evaporator power
3. Evaporator effectiveness.

This data is presented on figures 17,18, and 19. Noting figures 17 and 18, it is clear that the response of the U prototype is superior to the response of the L prototype. The explanation for this seems to be simply the details of each liquid reservoir

design (see figure 20). Transfer of heat with the reservoir is across the two resistances shown. In the case of the U prototype $R_{c\ fluid}$ is smaller than for the L prototype. This is because the thickness of the fluid layer is less for the U prototype than for the L prototype. The end result is that reservoir temperature can be changed more quickly for the Uprototype than for the L prototype (note that swings in evaporator power and evaporator effectiveness "follow" swings in the mean reservoir temperature).

6 ANALYSIS OF TEST RESULTS

6.1 Objectives of Analysis

The objective of this section is to attempt to answer the following question:

Why does the VCHPHX admit to control via varying the liquid reservoir temperature?

There is no apriori reason for this experimentally observed fact. Indeed, when one considers the governing equation for power transfer in conventional heat pipes,[2]

$$\dot{Q}_{max} = \frac{\rho K A L}{\mu_\ell} \cdot \frac{1}{\ell_{eff}} \cdot \left\{ \frac{2\sigma \cos\Theta}{r_c} + \rho g \ell_{eff} \sin\phi \right\} \tag{4}$$

it can be shown that $\dot{Q}_{max}$ decreases with increasing temperature of the heat pipe working fluid. At this point it becomes obvious that special circumstances must account for what the experimentor observes.

6.2 Heat Pipe Theory

Heat pipe operation depends on the flow of working fluid within a capillary structure to the evaporator and a subsequent return of the vapor to the condenser. The equation given above is derived from the following pressue balance:

Net Capillary Head = Liquid Pressure Drop
+Vapour Pressure Drop
+Body Force Head   (5)

The vapor pressure drop is usually negligible and the equation becomes:

Net Capillary Head = Liquid Pressure Drop
+Body Force Head   (6)

The capillary head is generated by the wick through which the liquid flows. It is a surface tension effect and for single layer screen mesh wicks is equal to:

$$\Delta P_{capillary\ max} = \frac{2\,\Upsilon\,\cos\Theta}{r_c} \tag{7}$$

The liquid pressure drop in the wick is given by Darcy's Law, essentially a definition for porosity, K:

$$\frac{dP_\ell}{dz} = \frac{\mu_\ell\,\dot{m}_\ell\,z}{K\,A_\ell} \tag{8}$$

The body force head is given by:

$$\frac{dP_{body}}{dz} = \pm\,\ell_\ell\,g\,\sin\phi \tag{9}$$

From equations 7,8, and 9 we can begin to examine the question posed in the light of conventional heat pipe theory.

6.3 The Linear Range of Control

The data presented in Chapter 5 showed that a large linear range of control existed for the VCHPHX. How can this be explained in the light of the governing equations? If one assumes a saturated wick, this fact cannot be explained by the theory. Therefore, the wick must not be saturated. There are several liquid profile models which one might propose.

These include:

   a)Receeded linear liquid profile within the wick
   b)Receeded sloped liquid profile within the wick
   c)The step wick model[4]
   d)Receeded curved liquid profile within the wick

Any one of these possibilities could explain the behavior which is observed. The net effect of any of these mechanisms for liquid profile variation would be to reduce the effective cross sectional area of the wick. Equation (8) shows that dP of the liquid increases with decreasing A_{eff}. For fixed $dP_{capillary}$ and dP_{body}, this means that $\dot{m}$ must decrease and hence Q must decrease.

6.4 The Question of Limits

   The asymptotes which are observed on the plot of condenser power versus mean reservoir temperature are not so easily explained in terms of the conventional heat pipe equations. Let us consider first the assymptote at the upper limit. A maximum condenser power is reached after which elevating the resevoir temperature serves no purpose. If the previous mode of control relied on variation of the wick thickness, it is clear that a maximum wick thickness must be reached at some point. This limit to wick thickness may result from one of the following conditions:

   a)   The wick is fully saturated
   b)   All the liquid in the reservoir has been expended.

Either of these conditions could explain the upper limit on condenser power transfer. Based on the expected overfill of the reservoirs, the former condition seems most likely.

The lower condenser power asymptote must result from a heat
pipe wick which is starved for liquid. An important question to
answer here is the following:

Does dryout occur along any portion of the evaporator?
A quantitative answer to this question can be seen on figure 15.
The temperature profile of the air leaving the evaporator is a
good indication of the onset of evaporator dyyout. Note that
the reduced temperature profile is plotted versus percent
evaporator length. As the reservoir temperature is reduced, the
curve indicates a reduced temperature profile which "climbs" the
evaporator wall toward the condenser. Since a reduced temperature
of unity indicates no heat transfer form the heat pipe in that
region, it seems safe to assume that the evaporator has dried out
in this region. This mode of heat pipe failure has also been
observed by Chun[5]. Granted now that partial dryout of the evap-
orator has occured, does this explain the much reduced condenser
power? Not to be overlooked is the effect of dryout on the heat
exchanger fin performance. As the liquid layer in the evapora-
tordries out, the ability of a "dry fin" to transport heat is
much reduced. This is because heat which was transported by the
condensing vapor must now be transported by the heat pipe wall,
a path of much greater resistance. Consider the case of the heat
pipe wick and liquid as shown in figure 16. The liquid layer has
dropped below the first fin. The evaporators first fin is no
longer "wet". Current flow in loop A is thus mainly via con-
duction along the heat pipe wall; through resistance R_c, current i2.

The liquid layer has not dried out at the second evaporator fin. Therefore, heat transfer along this path is mainly through resistor R_{HP}, current i3. R_{HP} is a film and conduction resistance combined; convection to the surface of the liquid layer and conduction across the liquid thickness. Heat transfer along the former path is much less than heat transfer along the alternate path due to R_{HP} being much less than R_c. This mode of power transfer modulation wet fin / dry fin, seems to play a major role in VCHPHX control.

Figure 15 also indicates another mode of control in operation. Note that once the entire evaporator wall is wetted, the liquid profile seems to thicken in an effort to saturate the wick. About 60% of the heat exchangers maximum power transfer is realized once the wick is saturated. How can the proposed model account for the last 40%? If the various resistances R_{HP} are independant variable resistors, then the proposed model can accomodate this experimental observation. R_{HP} would ideally be a function of only the liquid layer thickness at the fin in question.

7 CONCLUSIONS

The VCHPHX is clearly a viable approach to the problem of power transfer modulation in an air to air heat exchanger. The controlability which results from the use of temperature controlled liquid reservoirs is good when the U-prototype is considered. A further strong point of the U prototype is its ability to traverse the entire range of controlability without the need for reservoir cooling. The broad linear control range is ideal for automated control.

The question of the VCHPHX admission to control by variable reservoir temperature is largely answered. The 2 major modes of heat pipe-exchanger failure which are in operation seem to be:

a) wet fin / dry fin
b) Liquid layer recession

The incorporation of these failure modes into a heat pipe simulation presumes an ability to predict the liquid profile which results from a given set of heat pipe operating conditions. This prediction is the frontier of heat pipe research[4,5] and is the key to analytical design of the VCHPHX.

8 DEFINITION OF VARIABLES

A	Area (m^2)	
C	Centigrade	
K	Porosity	
L	Latent Heat (Joules/Kilogram)	
P	Power (Watts)	
Q	Heat Rate (Watts)	
R	Resistance $(m^2 C/Watt)$	
T	Temperature (C)	
r_c	Capillary Radius (m)	
g	Gravity (m/sec^2)	
h	Heat Transfer Coefficient $(Watts/m^2 C)$	
l_{eff}	Effective Length (m)	
$\dot{m}$	Mass Flow Rate (Kilograms/sec)	
z	Coordinate Length (m)	
Φ	Angle of Heat Pipe With Horizontal (degrees)	
θ	Contact Angle of Working Fluid (degrees)	
ρ	Density $(Kilograms/m^3)$	
σ	Surface Tension (Nt/m)	
μ	Viscosity (poise)	

Subscripts

c	Condenser
e	Evaporator
l	Liquid
v	Vapour

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APPENDIX A - COMPUTER PROGRAM LISTING FOR DATA ACQUISITION

```
0000 DIM E(15),C(15)
0005 B=2.2245-5
0006 T1=42
0007 T2=41
0010 REM GRID TEMP OUTPUT SWITCHED
0011 DIM A(43)
0015 REM RC(1).
0020 PRINT "REFERENCE TEMPERATURE"
0025 INPUT T1
0026 PRINT "PELTIER POWER"
0017 INPUT R1
0016 T2=0
0017 T3=0
0023 POKE( 45059,49); # OF RELAYS
0030 POKE( 45061,4); # OF CHANNELS
0040 POKE( 45058,1); # OF LOOPS
0050 POKE( 41049,8)
0060 POKE( 73,97); HIGH BYTE OF ASLGP ADDRESS
0070 POKE( 74,213); LOW BYTE OF ASLGP ADDRESS
0080 S0=USER(S0)
0090 REM INITIATE SCAN
0100 POKE( 73,98)
0110 POKE( 74,66)
0120 S1=USER(S1)
0130 REM ADJUST LAST THREE VALUES
0140 X1=PEEK(45071)
0150 X2=PEEK(45072)
0160 A=((X1*256)+X2)-6
0170 FOR I=1 TO 3
0180 X1=PEEK(A)
0190 X2=PEEK(A+1)
0200 V=((X1*256)+X2)/40
0210 GOSUB 1000
0220 NEXT I
0230 REM PRINT OUT DATA
0240 FOR I=1 TO 43
0250 J=I-1
0260 K=2*J
0270 A=46060+K
0280 X1=PEEK(A)
0290 X2=PEEK(A+1)
0300 V=((X1*256)+X2)
0310 A(I)=V
0320 NEXT I
0322 A(41)=(A(41)-01)*.7355
0323 A(42)=(A(42)-02)*.2440
0318 PRINT A(41),A(42)
0350 GOTO 1070
0900 REM SUBROUTINE 1000
1000 V=V/100
1010 V=INT(V)
1020 V=V-V1*256
1030 POKE( A,V1)
1040 POKE( A+1,V)
1050 I=I+1
1060 RETURN
```

```
1086    A(I)=X/100
1088 NEXT I
1089 FOR I=1 TO 7
1090    K=I+1
1092    L=I+9
1094    C(I)=A(L)
1096    T3=T3+C(I)
1100    E(I)=A(K)
1102    T2=T2+E(I)
1110 NEXT I
1120 FOR I=8 TO 15
1130    K=I+17
1140    E(I)=A(K)
1142    T2=T2+E(I)
1144    L=I+25
1146    C(I)=A(L)
1148    T3=T3+C(I)
1150 NEXT I
1151 GOSUB 1300
1152 PRINT
1153 PRINT
1154 PRINT "        EVAPORATOR TEMPERATURE MAP"
1156 PRINT "           DEGREES CENTIGRADE"
1157 PRINT
1159 FOR I=1 TO 5
1170    K=16-3*I
1180 PRINT E(K),E(K+1),E(K+2)
1182 NEXT I
1184 PRINT
1187    T2=T2/15
1188    T2=T2*100
1190    T2=INT(T2)
1192    T2=T2/100
1193 PRINT "TEIN=   "; A(19)
1194 PRINT "TAVE=") T2
1195    D1=(356/(273.2+A(20)))
1196    D2=(350/(273.2+A(17)))
1197    C9=.005667*SQR(A(41)/D1)+.005
1198    E9=.09678*SQR(A(42)/D2)+.008
1200    E1=E9*100*(A(19)-T2)
1201 IF C9>E9 GOTO 1204
1202    Z9=E9
1203 GOTO 1205
1204    Z9=C9
1205    Q=Z9*100*(A(19)-A(20))
1207    E6=(E1/Q)*100
1210    C1=C9*100*(A(20)-T3)
1211    C6=-(C1/Q)*100
1220    P1=C9*100*(A(17)-A(18))
1221    C6=C6*100
1222    E6=E6*100
1223    C6=INT(C6)
1224    E6=INT(E6)
1225    C6=C6/100
1226    E6=E6/100
1230    L1=E1+C1+P1+P1
1231    L2=L1
1232    GOTO 1297
```

```
1460 NEXT I
1472  T3=T3/15
1474  T3=T3*100
1476  T3=INT(T3)
1478  T3=T3/100
1480 PRINT
1483 PRINT "TCIN=   "; A(20)
1484 PRINT "TCAVE=  "; T3
1486 RETURN
1487 PRINT
1498 PRINT
1520 PRINT "        RESERVOIR TEMPERATURES"
1540 PRINT "          DEGREES CENTIGRADE"
1560 PRINT
1570  M2=A(21)+A(22)+A(23)+A(24)
1571  M2=M2/4
1580 PRINT "ROW1   ";A(21)
1600 PRINT "ROW2   ";A(23)
1620 PRINT "ROW3   ";A(22)
1640 PRINT "ROW4   ";A(24)
1650 PRINT
1652 PRINT "MEAN   ";M2
1660 PRINT
1662 PRINT
1666 PRINT "      PELTIER COOLER TEMPERATURES"
1668 PRINT "          DEGREES CENTIGRADE"
1670 PRINT
1672 PRINT "INLET TEMP=  ";A(17)
1674 PRINT "EXIT TEMP=   ";A(18)
1680 PRINT
1689 PRINT C9,E9
1690  R7=C9/E9
1692 PRINT "MASS FLOW RATIO";R7
1694  L7=(T2-M2)/(P1+R1)
1695  L7=L7*(-1)
1696 PRINT "LOSS COEFFICIENT";L7
1700 PRINT
1720 PRINT "            FIRST LAW ANALYSIS"
1730 PRINT "            POWER IN WATTS"
1740 PRINT
1760 PRINT "CONDENSER POWER    ";C1
1780 PRINT "EVAPORATOR POWER   ";E1
1810 PRINT "PELT COOLER POWER  ";P1
1815 PRINT "PELT CELL POWER    ";R1
1820 PRINT "TRANSFER WITH AMB  ";L1
1840 PRINT
1850 PRINT
1880 PRINT "    HEAT EXCHANGER EFFECTIVENESS"
1890 PRINT "            PERCENT"
1900 PRINT
1920 PRINT "CONDENSER EFFECTIVENESS    ";C6
1940 PRINT "EVAPORATOR EFFECTIVENESS   ";E6
1960 PRINT
1961 GOTO 10
1980 END

READY
>
```

APPENDIX B - WORKING FLUID PROPERTIES

Property Data For Methyl Chloride

C	Liquid Density (K/m^3)	Vapour Density (K/m^3)
1	957.883068	6.3568821
2	955.787546	6.6371048
3	953.712342	6.9075327
4	951.656365	7.1690304
5	949.618525	7.4224625
6	947.597731	7.6686936
7	945.592893	7.9085883
8	943.602918	8.1430112
9	941.626718	8.3728269
10	939.6632	8.5989
11	937.711275	8.8220951
12	935.76985	9.0432768
13	933.837836	9.2633097
14	931.914141	9.48305641
15	929.997675	9.7033875
16	928.087347	9.92516161
17	926.182067	10.1492453
18	924.280742	10.3765032
19	922.382284	10.6077999
20	920.4856	10.844
21	918.5896	11.0859681
22	916.693194	11.3345688
23	914.795289	11.5906667
24	912.894797	11.8551264
25	910.990625	12.1288125
26	909.081683	12.4125896
27	907.166881	12.7073223
28	905.245127	13.0138752
29	903.31533	13.3331129
30	901.3764	13.6659
31	899.427246	14.0131011
32	897.466778	14.3755808
33	895.493903	14.7542037
34	893.507533	15.1498344
35	891.506575	15.5633375
36	889.489939	15.9955776
37	887.456535	16.4474193
38	885.405271	16.9197272
39	883.335056	17.4133659
40	881.2448	17.9292
41	879.133412	18.4680941
42	876.999802	19.0309128
43	874.842878	19.5185207
44	872.661549	20.2317824
45	870.454725	20.8715625
46	868.221315	21.5387256
47	865.960229	22.2341362
48	863.670375	22.9586592
49	861.350662	23.7131589
50	859	24.4985
51	856.617298	25.3155471
52	854.201456	26.1651648
53	851.751411	27.0482177

56	844.185011	29.9066336
57	841.587163	30.9320733
58	838.949633	31.9952712
59	836.271348	33.0970919
60	833.5512	34.2384
61	830.788104	35.4200602
62	827.98097	36.6429369
63	825.128705	37.9078948
64	822.230221	39.2157984
65	819.284425	40.5675126
66	816.290227	41.9639017
67	813.246537	43.4058384
68	810.152263	44.8941833
69	807.006314	46.4297649
70	803.8076	48.0135001
71	800.55503	49.6462332
72	797.247514	51.3288289
73	793.88396	53.0621518
74	790.463277	54.8470665
75	786.984375	56.6844376
76	783.446163	58.5751297
77	779.847551	60.5200074
78	776.187446	62.5199353
79	772.46476	64.575778
80	768.6784	66.6884001
81	764.827276	68.8586662
82	760.910298	71.0874409
83	756.926373	73.3755889
84	752.874413	75.7239746
85	748.753325	78.1334626
86	744.562019	80.6049178
87	740.299404	83.1392045
88	735.96439	85.7371874
89	731.555886	88.399731
90	727.0728	91.1277002
91	722.514042	93.9219593
92	717.878522	96.783373
93	713.165148	99.7128059
94	708.372829	102.711123
95	703.500475	105.779188
96	698.546995	108.917866
97	693.511299	112.128021
98	688.392295	115.410519
99	683.188892	118.766224
100	677.9	122.196

metals

The compatibility of methyl chloride with certain commonly used metals at room temperature is given in the table below:

Material	Compatibility
Zinc and its alloys	B
Aluminum and its alloys	B (*)
Magnesium and its alloys	D
Asbestos	A
Iron	A
Galvanized iron	B
Carbon steels	A
Stainless steels	A
Copper and its alloys	A
Bronze	A

A: Good resistance to dry methyl chloride
B: Poor resistance to dry methyl chloride
(*): With aluminum, methyl chloride forms methylated aluminum compounds, which are hazardous and spontaneously flammable in air.

In the presence of moisture, metals and alloys employed must be resistant to hydrochloric acid.

elastomers

The following table shows the linear expansion (%) of some elastomers when immersed in liquid methyl chloride for several days at room temperature:

Material	Dilatation Expansion
Buna N ®	35
Buna S ®	20
Butyl rubber	16
Polysulfide type elastomer	11
Natural rubber	26
Neoprene GN ®	22
Viton ®	(*)
Hypalon ®	(*)
Polyvinyl alcohol	(*)

(*) slight swelling, satisfactory for use

plastics

The compatibility of dry methyl chloride with some plastics is given in the table below:

Material	Compatibility
Teflon ®	A
Kel-F ®	A
Polyvinyl chloride	B
Rigid polyethylene	B
Cellulose	B

A: good
B: poor

uses

Methyl chloride is used in the following applications:
· Therapeutic treatment of local anesthesia
· Refrigerating agent in the refrigeration industry
· Propellant gas in the aerosol industry
· Chemical industry: methylation agent in organic synthesis for the production of tetramethyl lead, silicones and butyl rubber

It also serves as a solvent or extraction agent for heat-sensitive products.

---

métaux

La compatibilité du chlorométhane sec avec certains métaux usuels, pour les températures ordinaires, est donnée dans le tableau ci-dessous

Matériau	Compatibilité
Zinc et alliages	B
Aluminium et alliages	B (*)
Magnésium et alliages	D
Amiante	A
Fer	A
Fer galvanisé	B
Aciers ordinaires	A
Aciers inoxydables	A
Cuivre et alliages	A
Bronze	A

A bonne résistance au chlorométhane sec
B mauvaise résistance au chlorométhane sec
(*) avec l'aluminium, le chlorométhane forme des composés méthylés de l'aluminium, produits dangereux, spontanément inflammables à l'air.

Pour le chlorométhane en présence d'humidité, les métaux et alliages employés devront être résistants à l'acide chlorhydrique.

elastomères

Dilatation linéaire (*) des élastomères suivants plongés dans le chlorométhane liquide pendant plusieurs jours à la température ordinaire.

Matériau	Dilatation
Buna N ®	35
Buna S ®	20
Caoutchouc butyle	16
Elastomère type polysulfure	11
Caoutchouc naturel	26
Néoprène GN ®	22
Viton ®	(*)
Hypalon ®	(*)
Alcool polyvinylique	(*)

(*) dilate légèrement, utilisable

matières plastiques

La compatibilité du chlorométhane sec avec quelques matières plastiques est donnée par le tableau suivant:

Matériau	Compatibilité
Téflon ®	A
Kel-F ®	A
Chlorure de polyvinyle	B
Polyéthylène rigide	B
Cellulose	B

A: bonne
B: mauvaise

utilisations

Le chlorométhane est employé:
· en thérapeutique, pour les anesthésies locales
· comme agent réfrigérant dans l'industrie du froid
· comme propulseur dans l'industrie des aérosols
· dans l'industrie chimique, comme agent de méthylation en synthèse organique, pour la fabrication du plomb tétraméthyle, des silicones, du caoutchouc butyl

Il est aussi employé comme solvant ou agent d'extraction de produits sensibles à la chaleur.

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stability

Methyl chloride is stable at room temperature in the absence of moisture, but decomposes at temperatures above 400°C, generating toxic hydrogen chloride, chlorine and, in certain cases, carbon monoxide and phosgene.

flammability [9]

In air:

- Flammability limits at 20°C, 1 atm
  lower: 8.1%
  upper: 17.2%
- Minimum autoignition temperature at 1 atm: 632°C

biological properties [6 - 7 - 8 - 9]

Methyl chloride is a toxic, narcotic gas, which penetrates the organism through the respiratory system.
The degree of intoxication varies and the main symptoms are the following:

- For slight poisoning: state of drunkenness with headaches, vertigo, nausea, vomiting and hiccups.
- For more serious poisoning: mental confusion and, in some cases, temporary loss of consciousness, followed by cerebellar and striated neurological symptoms.
- For severe intoxication: violent abdominal pains with vomiting, diarrhea, staggering, trembling, extreme nervousness, mental confusion, followed by a coma sometimes accompanied by fever, convulsions and death.

Toxic kidney and liver affections have also been observed.
Apparent recovery from what appears to be a harmless respiratory intoxication may be followed by serious, prolonged, delayed effects after a period lasting from a few days to a few weeks. The neurological consequences are very serious.
Amnesia may be observed during convalescence.
The following threshold limit value is recommended for methyl chloride, as the concentration in air to which nearly all workers may be exposed during an 8-hour workday and 40-hour workweek, without adverse effects:

100 ppM-vol	ou or
210 mg m⁻³	

Repeated exposure is dangerous as methyl chloride is only eliminated slowly by the body, in which it is converted into hydrochloric acid and methyl alcohol.

Contact of the skin and eyes with concentrated vapor or liquid methyl chloride causes a condition resembling frostbite, the formation of blisters and, occasionally, gangrene.

recommendations

Make sure that persons affected by nervous and kidney liver problems refrain from contact with methyl chloride.

first aid suggestions

In case of intoxication, summon medical aid immediately, and remove the victim from the contaminated zone. If necessary, practice resuscitation.

precautions in handling and storage

CAUTION: METHYL CHLORIDE IS A TOXIC, FLAMMABLE GAS WHICH IS HEAVIER THAN AIR. NEVER USE IT WITHOUT REFERRING TO CHAPTER III

leak detection and analysis

Methyl chloride is colorless and has an odor of ether.
Before using equipment containing methyl chloride test the assembly with a leak detector.

Leaks may be detected:

- by the application of a surface-active substance at suspected points.
- by injecting the gas into a flame in the presence of copper, giving a green color (halide lamp).
- by means of a detection instrument for flammable gases, based on the measurement of variations in resistance of a platinum palladium alloy wire, which acts as a catalyst to oxidize the methyl chloride

Atmospheres containing methyl chloride may be analyzed by the following means:

- Introduction of the air to be analyzed, previously saturated with moisture, into a silica tube heated to redness. The hydrochloric acid liberated is determined by absorption in a silver nitrate solution.
- adsorption of gases on activated charcoal or silica gel followed by gravimetric analysis.
- combustion in a microburner followed by titrimetric or conductimetric analysis.

The following industrial analytical methods are used: gas phase chromatography (especially with an electron capture detector)
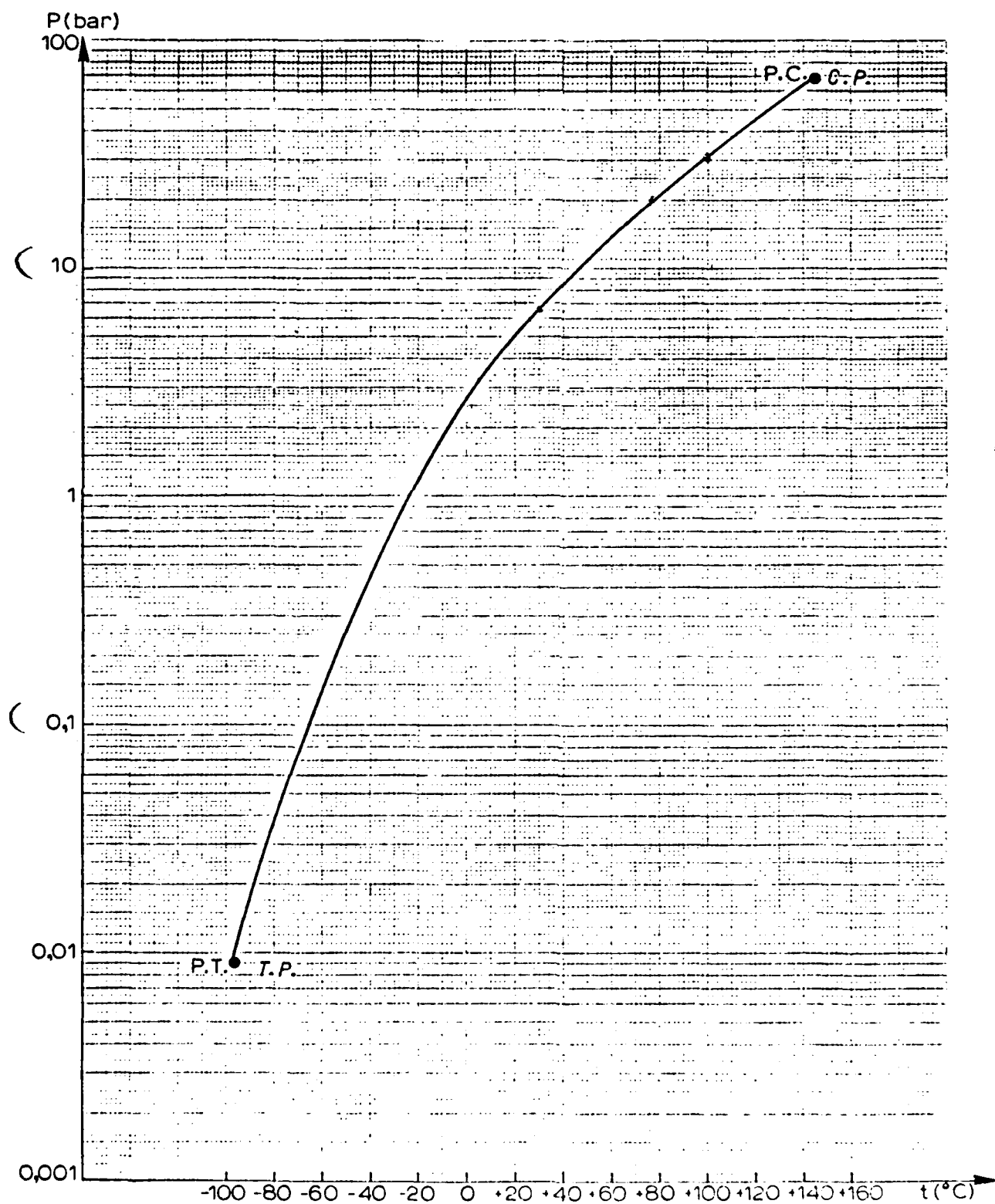
- mass spectrometry
- plasma emission spectrometry

material of construction [9 10 11 12 15]

Methyl chloride is hydrolysed in water and under the action of heat, to form hydrochloric acid and methyl alcohol.
Any installation designed to contain methyl chloride must be subjected simultaneously to the following

- Storing at about 120°C for at least 30 minutes
- Vacuum pumping (P ≤ 10⁻² mm Hg) in preference to dry gas flushing.

---

stabilité

Le chlorométhane, stable à température ordinaire et en absence d'humidité, se décompose à des températures supérieures à 400°C avec émission de produits toxiques: chlorure d'hydrogène, chlore, et dans certaines conditions, oxyde de carbone et phosgène.

inflammabilité [9]

Dans l'air:

- Limites d'inflammabilité à 20°C, 1 atm
  inférieure: 8.1%
  supérieure: 17.2%
- Température minimale d'auto-inflammation à 1 atm: 632°C

propriétés biologiques [6 - 7 - 8 - 9]

Le chlorométhane est un gaz toxique, narcotique, qui pénètre dans l'organisme par les voies respiratoires.
Le degré d'intoxication est variable et les principaux symptômes sont:

- pour les intoxications légères, état d'ébriété avec céphalées, vertiges, nausées ou vomissements, hoquets.
- pour les intoxications plus graves, troubles confusionnels et inconscience passagère, une perte de connaissance transitoire, puis des manifestations neurologiques cérébelleuses et striées
- pour les intoxications sévères, des douleurs abdominales violentes avec vomissements, diarrhées, démarche chancelante, tremblements, nervosité extrême, confusion mentale précédant un coma parfois fébrile ou convulsif mortel

On a également noté des troubles rénaux et des hépatites toxiques.
Un apparent rétablissement de ce qui semble être une intoxication respiratoire anodine peut être suivie d'effets graves sérieux et prolongés jours au delà de quelques jours à quelques semaines. Les séquelles neurologiques sont lourdes. Une amnésie peut s'observer au cours de la convalescence
La concentration maximale admissible recommandée pour le chlorométhane dans les atmosphères des locaux industriels, pour tant des expositions de 8 heures par jour pendant 5 jours par semaine sans effets décelables pour la plupart des individus est de:

100 ppM-vol	ou or
210 mg m⁻³	

Des expositions répétées sont dangereuses car le chlorométhane s'élimine lentement du corps, dans lequel il se transforme en acide chlorhydrique et alcool méthylique

Le contact avec la peau et les yeux, de vapeurs concentrées de chlorométhane liquide, provoque des gelures, la formation d'ampoules et, éventuellement, de la gangrène.

recommandations

Veillez à ce que des sujets présentant des affections nerveuses et hépato-rénales ne puissent être en contact de chlorométhane.

traitement des intoxications accidentelles

En cas d'intoxication, prévenir le service médical, retirer la victime de la zone polluée. Mettre en oeuvre si nécessaire les méthodes de réanimation.

précautions pour le stockage et la manipulation

ATTENTION: LE CHLOROMÉTHANE EST UN GAZ TOXIQUE, INFLAMMABLE, PLUS LOURD QUE L'AIR NE JAMAIS UTILISER DE CHLOROMÉTHANE SANS AVOIR CONSULTÉ LE CHAPITRE III

détection des fuites – analyse

Le chlorométhane est incolore et a une odeur éthérée.
Avant utilisation d'un appareillage devant contenir du chlorométhane, tester le montage avec un détecteur de fuite.

On peut déceler les fuites:

- par formation de bulles avec un agent tensio-actif
- en injectant ce gaz dans une flamme en présence de cuivre; on obtient une coloration verte (lampe haloïde).
- à l'aide d'un détecteur spécifique de gaz inflammable basé sur la mesure de la variation de résistance d'un fil de platine allié avec du palladium qui oxyde catalytiquement le chlorométhane

Les atmosphères contenant du chlorométhane peuvent être dosées par:

- passage de l'air à analyser préalablement saturé de vapeur d'eau, dans un tube de silice porté au rouge. L'acide chlorhydrique libéré est ensuite dosé par absorption dans une solution de nitrate d'argent.
- adsorption des vapeurs sur du charbon actif ou du gel de silice et dosage par gravimétrie.
- combustion dans un microbrûleur et dosage par titrimétrie ou conductimétrie.

Les méthodes industrielles d'analyse sont les suivantes:

- chromatographie en phase gazeuse (en particulier avec détecteur à capture d'électrons)
- spectrométrie de masse
- spectrométrie d'absorption infra-rouge
- spectrométrie d'émission de plasma

compatibilité avec les matériaux

[9 10 11 12- 15]

Le chlorométhane s'hydrolyse dans l'eau pour donner, sous l'action de la chaleur, de l'acide chlorhydrique et de l'alcool méthylique.
Par conséquent, toute installation devant contenir du chlorométhane, doit subir simultanément:

- un étuvage aux environs de 120°C pendant au moins 30 minutes.
- un pompage sous vide (p ≤ 10⁻² mm Hg) plutôt qu'un balayage de gaz sec.

pression de vapeur saturante [1] | *vapor pressure [1]*

facteur de compressibilité [2–3] | compressibility factor [2–3]

t(°C) \ P(bar)	1	2	3	4	5	7	8	9	6
15	0,9858	0,9711	0,9560	0,9270					
50	0,9840	0,9726	0,9590	0,9450	0,9308	0,9030	0,8872	0,8712	

chaleur spécifique [4]
$c_p = 0,193 \ kcal.kg^{-1}.K^{-1}$ pour le gaz parfait à 25°C

viscosité
(1 atm)
(multiplier ces valeurs par 10^{-5} pour obtenir des poises)

heat capacity [4]
$c_p = 0,193 \ kcal.kg^{-1}.K^{-1}$ for the perfect gas at 25°C

viscosity
(1 atm)
(multiply these values by 10^{-5} to obtain poises)

Température (°C) / Temperature	Viscosité (*) / Viscosity
0	9,89
15	10,44
50	11,73
100	13,55

(*) calcul L'AIR LIQUIDE | (*) L'AIR LIQUIDE calculation

conductivité thermique
(1 atm)
(multiplier ces valeurs par 10^{-5} pour obtenir des $cal.cm^{-1}.s^{-1}.K^{-1}$)

thermal conductivity
(1 atm)
(multiply these values by 10^{-5} to obtain $cal.cm^{-1}.s^{-1}.K^{-1}$)

Température (°C) / Temperature	Conductivité (*) / Conductivity
0	2,51
15	2,71
50	3,19
100	3,97

(*) calcul L'AIR LIQUIDE | (*) L'AIR LIQUIDE calculation

tension superficielle [13]
(interface liquide-vapeur)
$\gamma = 16,2 \ dynes.cm^{-1}$ à 20°C

surface tension [13]
(liquid-gas interface)
$\gamma = 16,2 \ dynes.cm^{-1}$ at 20°C

indice de réfraction [13]
(raie D du sodium)
n = 1,3389 pour le liquide à 20°C, $P \sim P_{sat}$.

refractive index [13]
(sodium D line)
n = 1,3389 for the liquid at 20°C, $P \sim P_{sat}$.

solubilité [13–14–16]
· Dans l'eau:
coefficient de Bunsen = 3,17 à 15°C
· Autres solvants:
Le chlorométhane est soluble dans l'alcool, l'éther, le chloroforme, l'acide acétique, l'acétone et le benzène.

solubility [13–14–16]
· In water:
Bunsen coefficient = 3,17 at 15°C
· Other solvents:
Methyl chloride is soluble in alcohol, ether, chloroform, acetic acid, acetone and benzene.

monochlorométhane
CH₃Cl

methyl chloride
CH₃Cl

Freon 40

Le monochlorométhane ou chlorure de méthyle on chlorométhane est un gaz dans les conditions ordinaires (15°C, 760 mm Hg).
C'est un gaz incolore, toxique et modérément inflammable. Il est livré liquéfié sous sa propre pression de vapeur
Les marques commerciales portent la référence R40

Methyl chloride, also known as chloromethane, is a gas in normal atmospheric conditions (15°C and 760 mm Hg). It is a colorless, toxic, slightly flammable gas. It is shipped as a liquefied gas under its own vapor pressure.
Commerical brands carry the designation R40

propriétés physiques / physical properties

| Formule chimique: | CH₃Cl |
| Masse molaire: | 50,488 g.mole⁻¹ |

| Formula: | CH₃Cl |
| Molecular weight: | 50,488 g.mole⁻¹ |

point triple [1] / triple point [1]

Température (K) (°C) Temperature	Pression (bar) Pressure	Chaleur latente de fusion (kcal.kg⁻¹) Latent heat of fusion
175,44 −97,71	0,0087	30,44

point d'ébullition [1] (1 atm) / boiling point [1] (1 atm)

Température (K) (°C) Temperature	Chaleur latente (kcal.kg⁻¹) Latent heat	Masse volumique liquide (kg.m⁻³) Liquid density	Masse volumique vapeur (kg.m⁻³) Gas density
249,39 −23,76	102,3	1002,9	2,55

1 litre de liquide libère 469 litres de gaz (détendu à 15°C, 1 bar)

1 liter of liquid liberates 469 liters of gas (expanded to 15°C, 1 bar)

point critique [1] / critical point [1]

Température (K) (°C) Temperature	Pression (bar) Pressure	Masse volumique (kg.m⁻³) Density
416,25 143,1	66,8	353

masse volumique [1] / density [1]

Température (°C) Temperature	Pression (bar) Pressure	Liquide (kg.m⁻³) Liquid	Vapeur (kg.m⁻³) Gas
0 (*)	2,56	960	6,066
15 (*)	4,20	930	9,704
50 (*)	10,92	859	24,51

(*) équilibre liquide-vapeur

(*) *liquid-gas equilibrium*
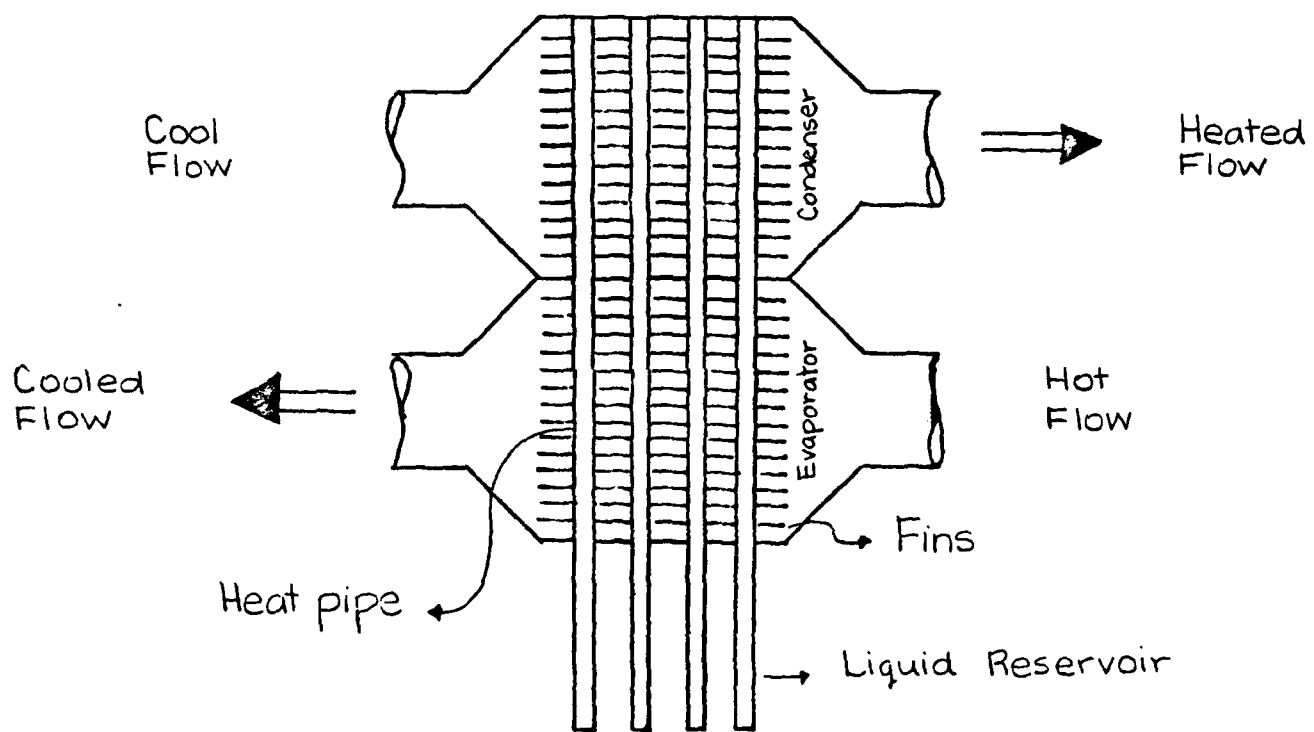
Figure 1   Variable Conductance Heat Pipe Heat Exchanger
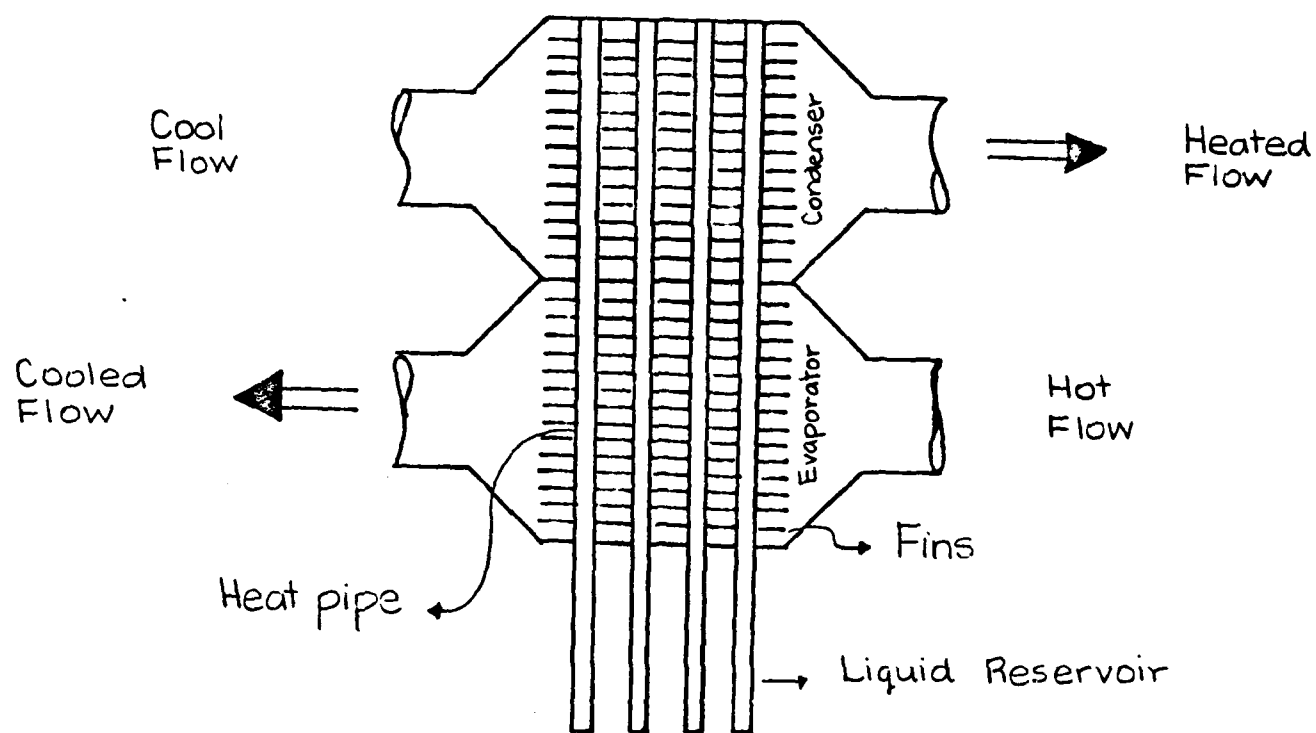
Figure 1 Variable Conductance Heat Pipe Heat Exchanger

Conventional
Heat Exchanger
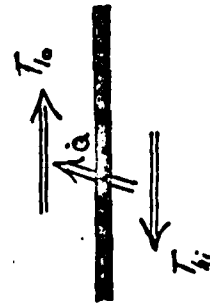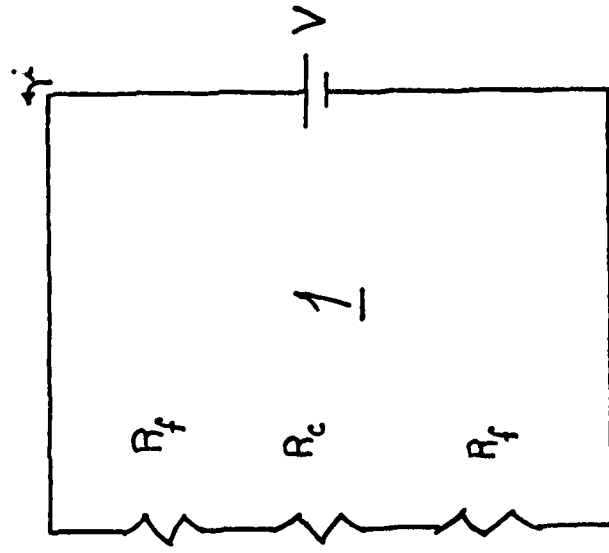
Heat Pipe
Heat Exchanger

$i = V/R$

$q = fA\Delta T$
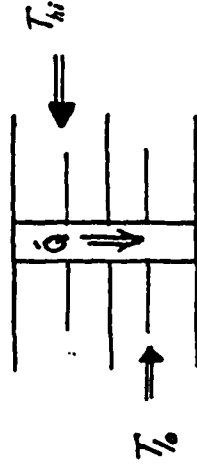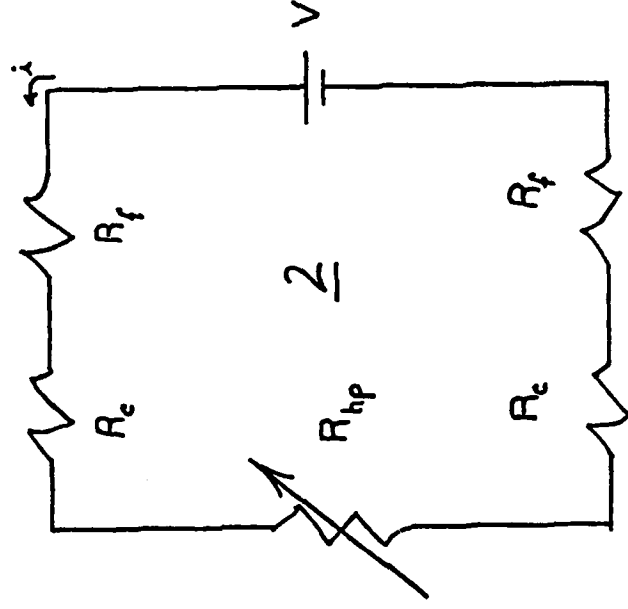
Figure 2 Electrical Circuit Equivalents Compared
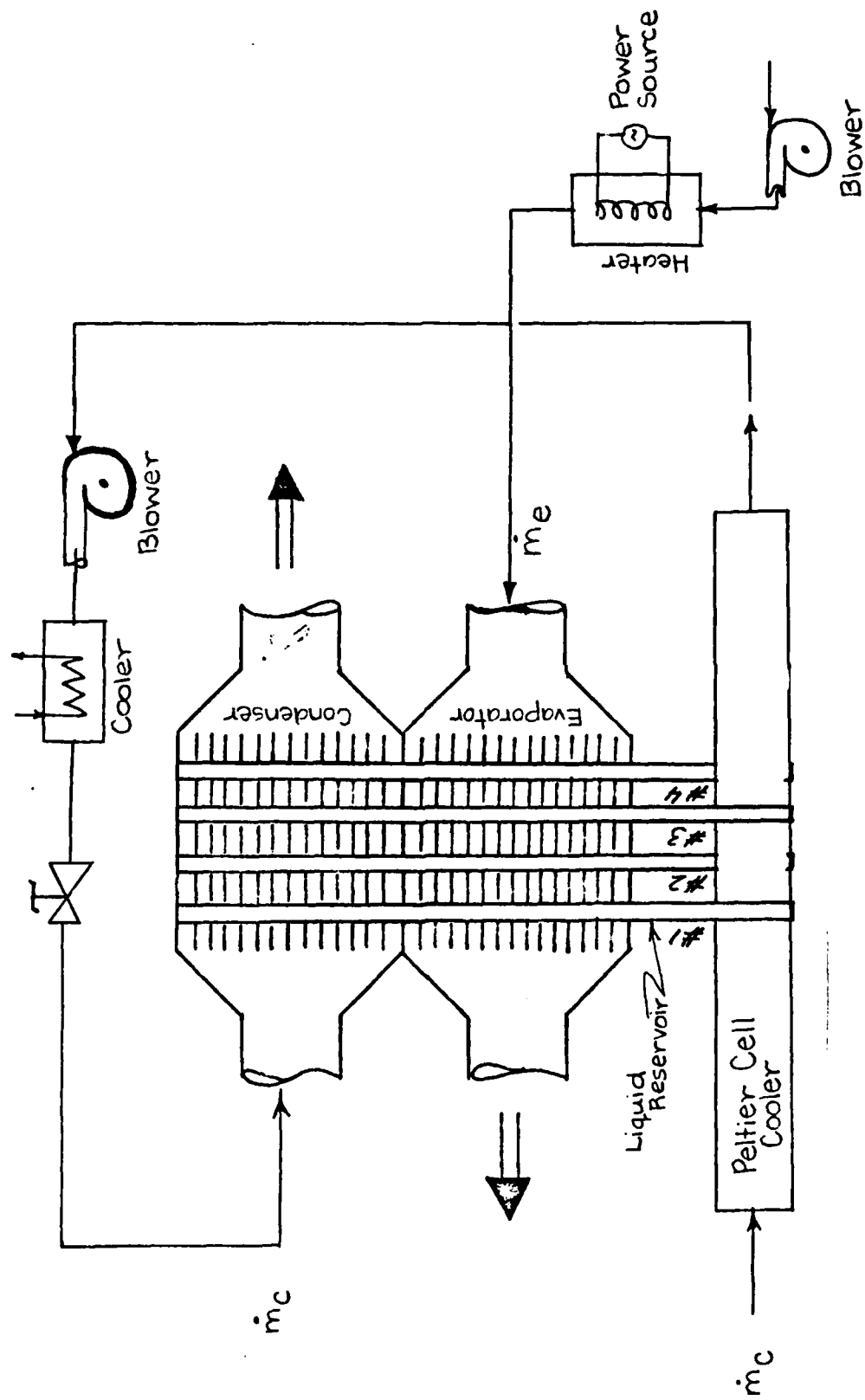
Figure 3A   Arrangement of System Components
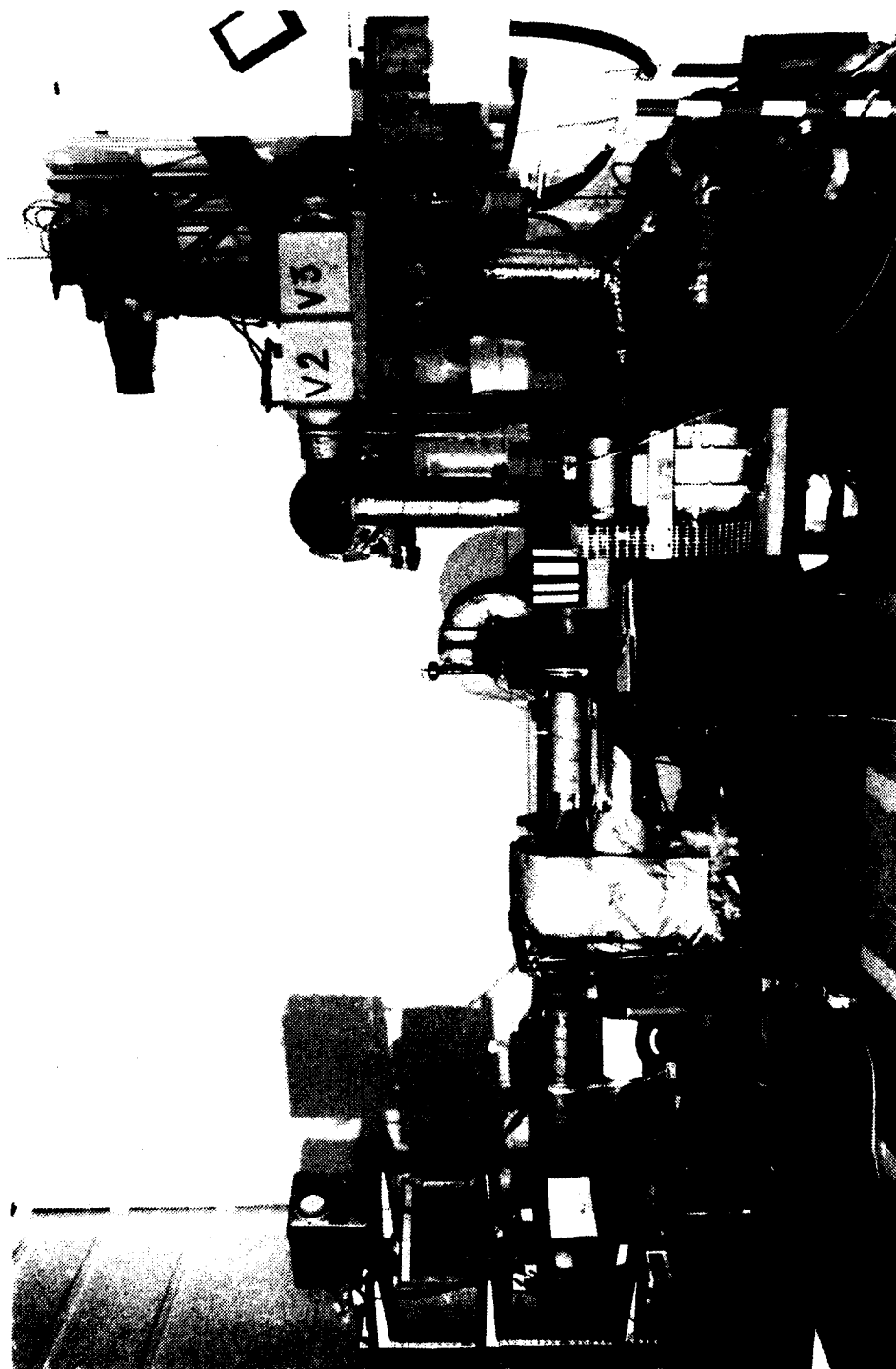
Figure 3B   The Experimental Facility

Figure 4   The Heat Exchanger Element
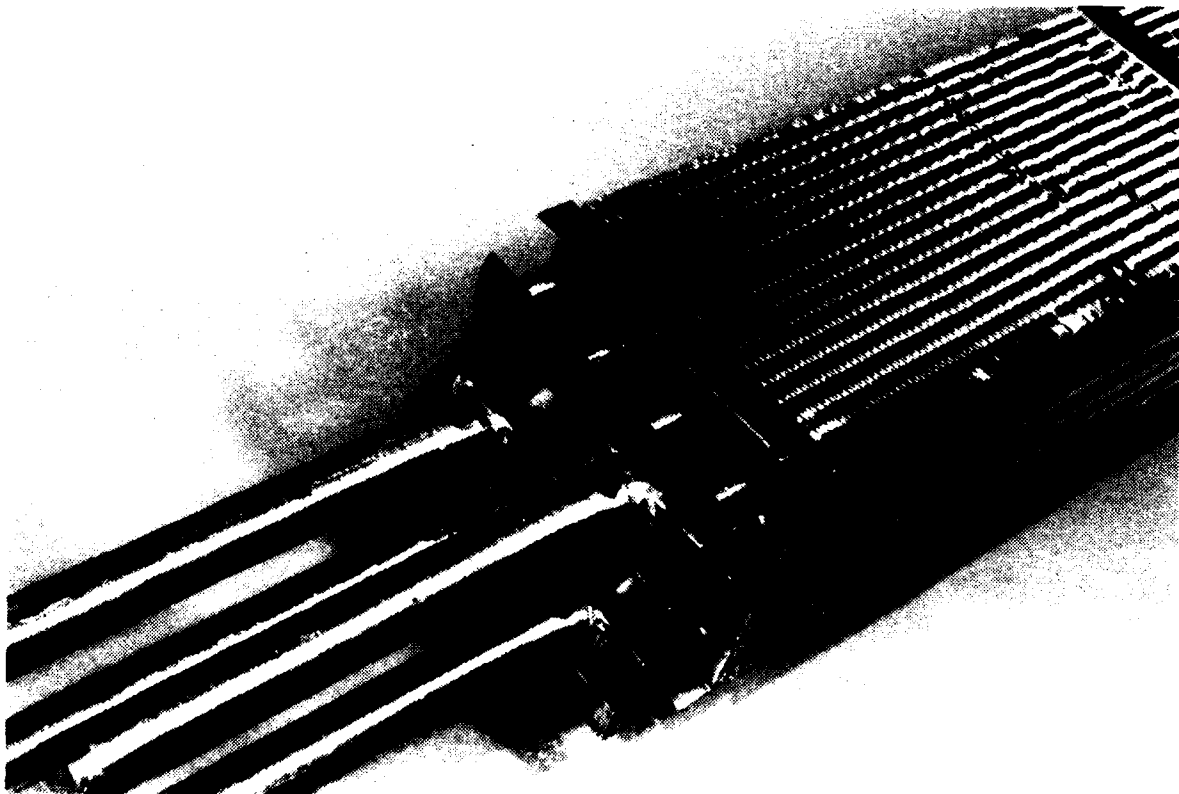
Figure 5 Detail of Reservoir Construction
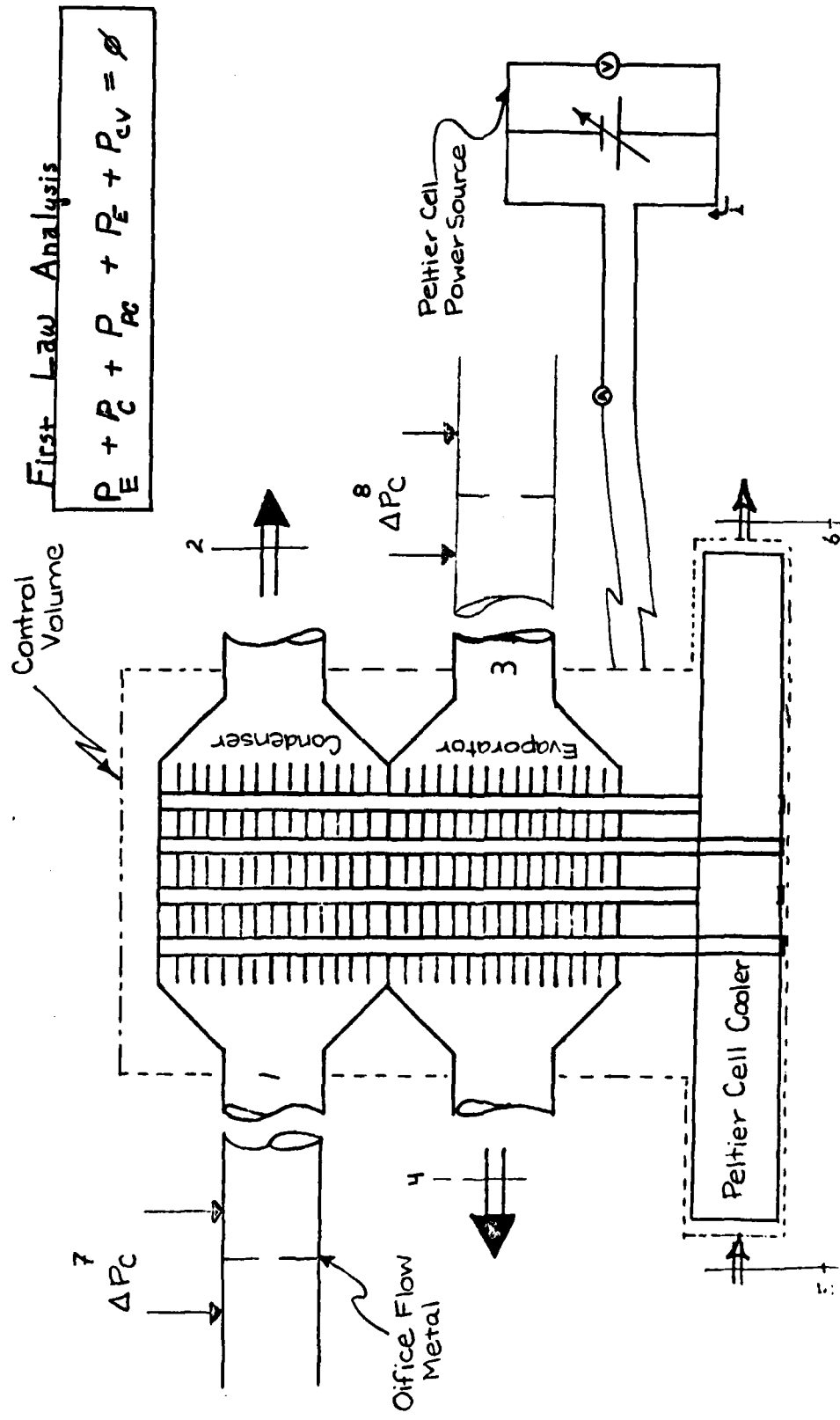
Figure 6 State Point Diagram
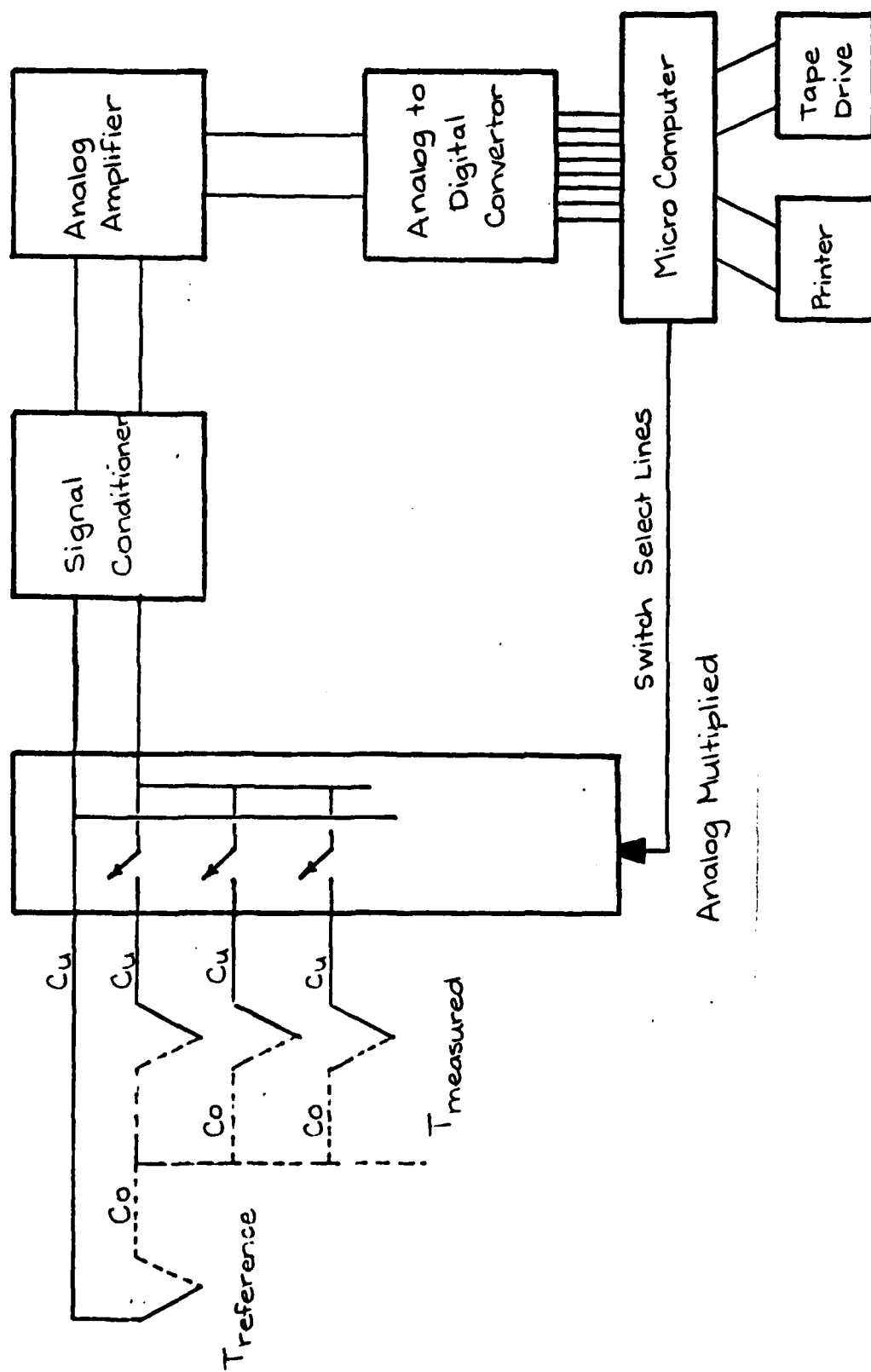
Figure 7   Schematic of Temperature Measurement System
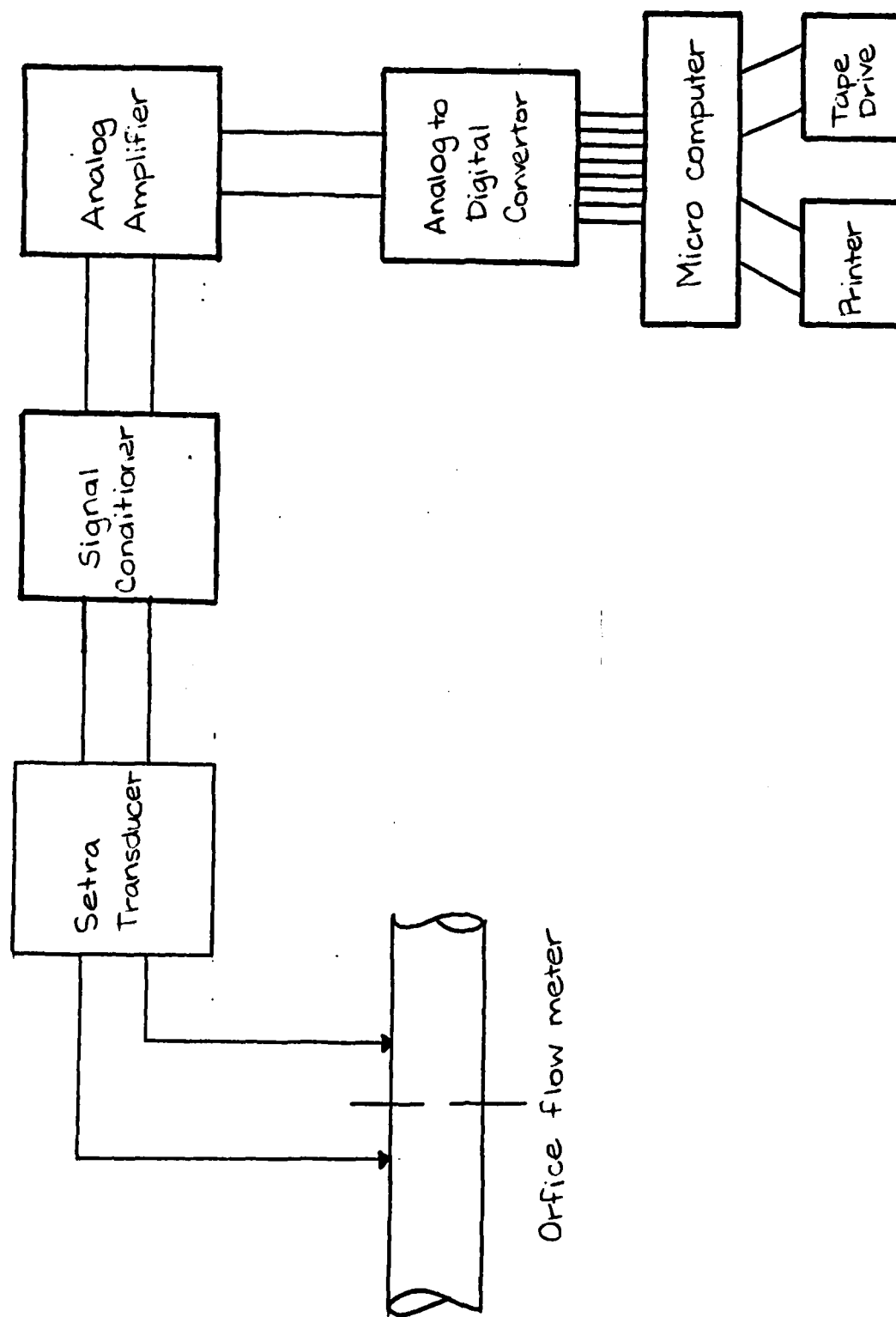
Figure 8 Schematic of Pressure Measurement System
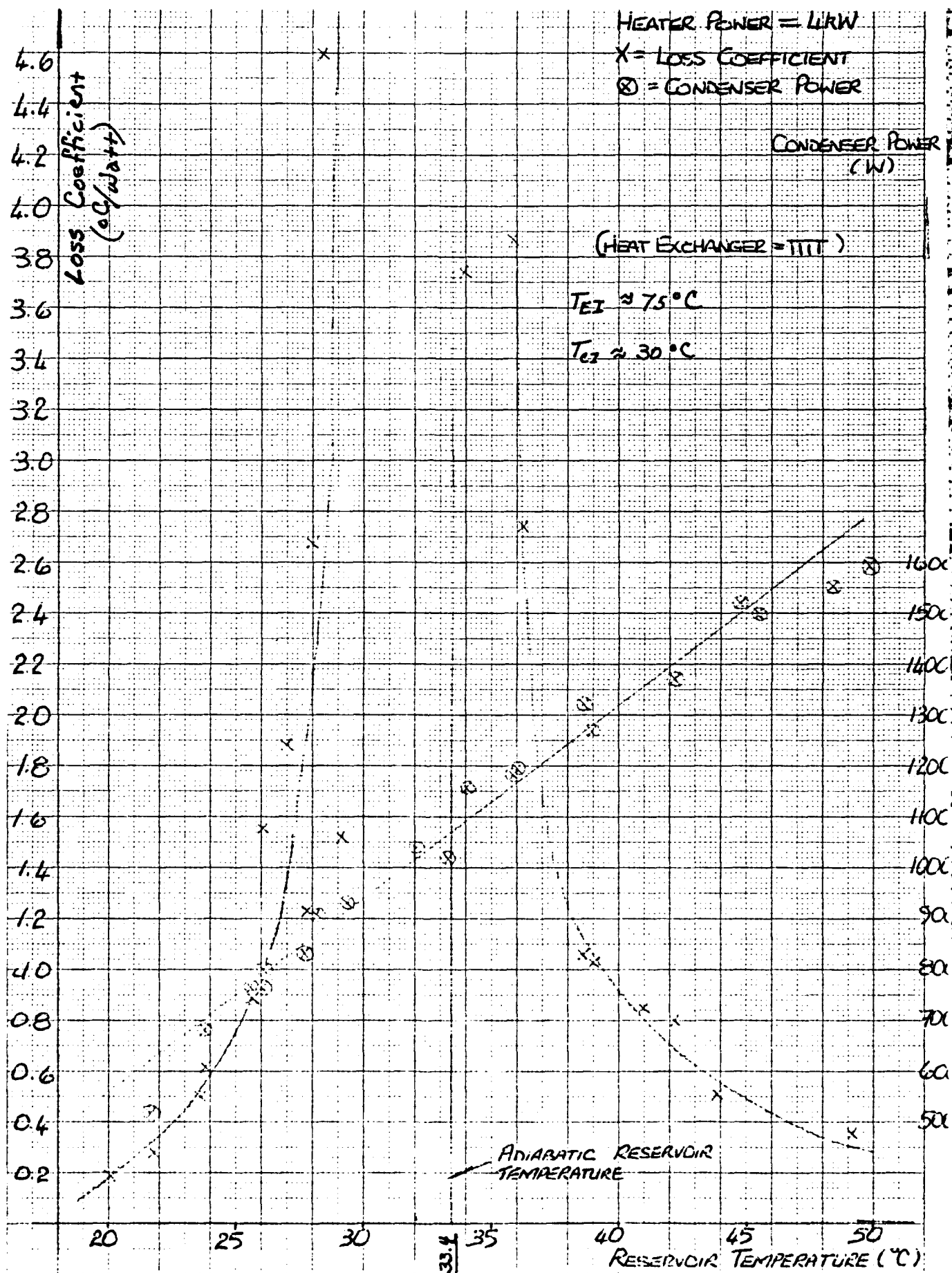
Figure 9   Performance Graph for The L-Prototype

PERFORMANCE GRAPH
for PROTOTYPE IIII

$T_{EI} \approx 75\,°C$

$T_{CI} \approx 30\,°C$

X = LOSS COEFFICIENT
⊙ = CONDENSER POWER

⊙ ADIABATIC TEMPERATURE

MEAN RESERVOIR TEMPERATURE
(°C)
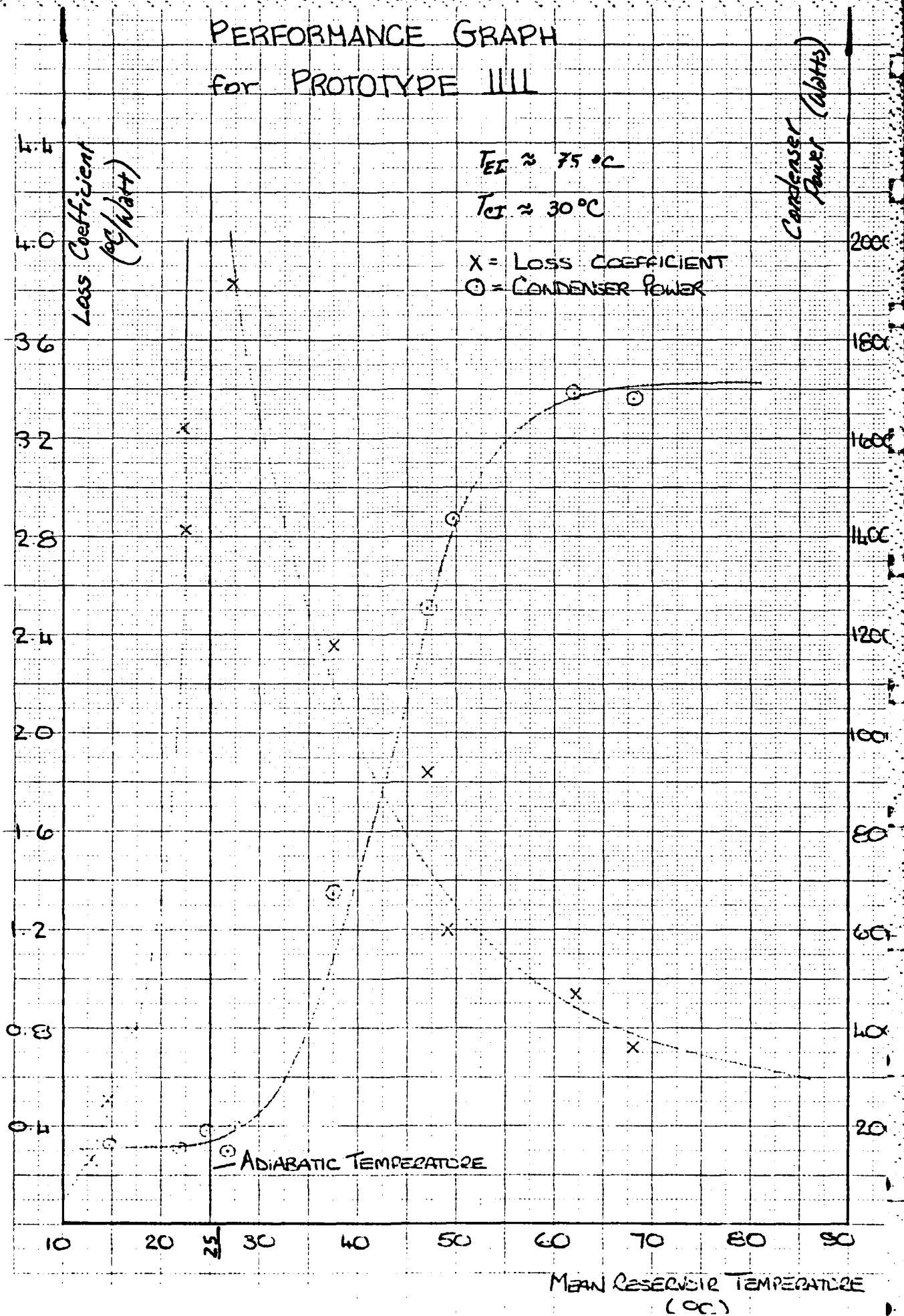
Figure 10 Performance Graph for The U-Prototype

EVAPORATOR POWER

$T_{EI} \approx 120\,°C$

$T_{CI} \approx 30\,°C$

3600

3500

3400

3300

3200

3100

70   71   72   73   74   75   76   77   78   79   80

MEAN RESERVOIR TEMPERATURE
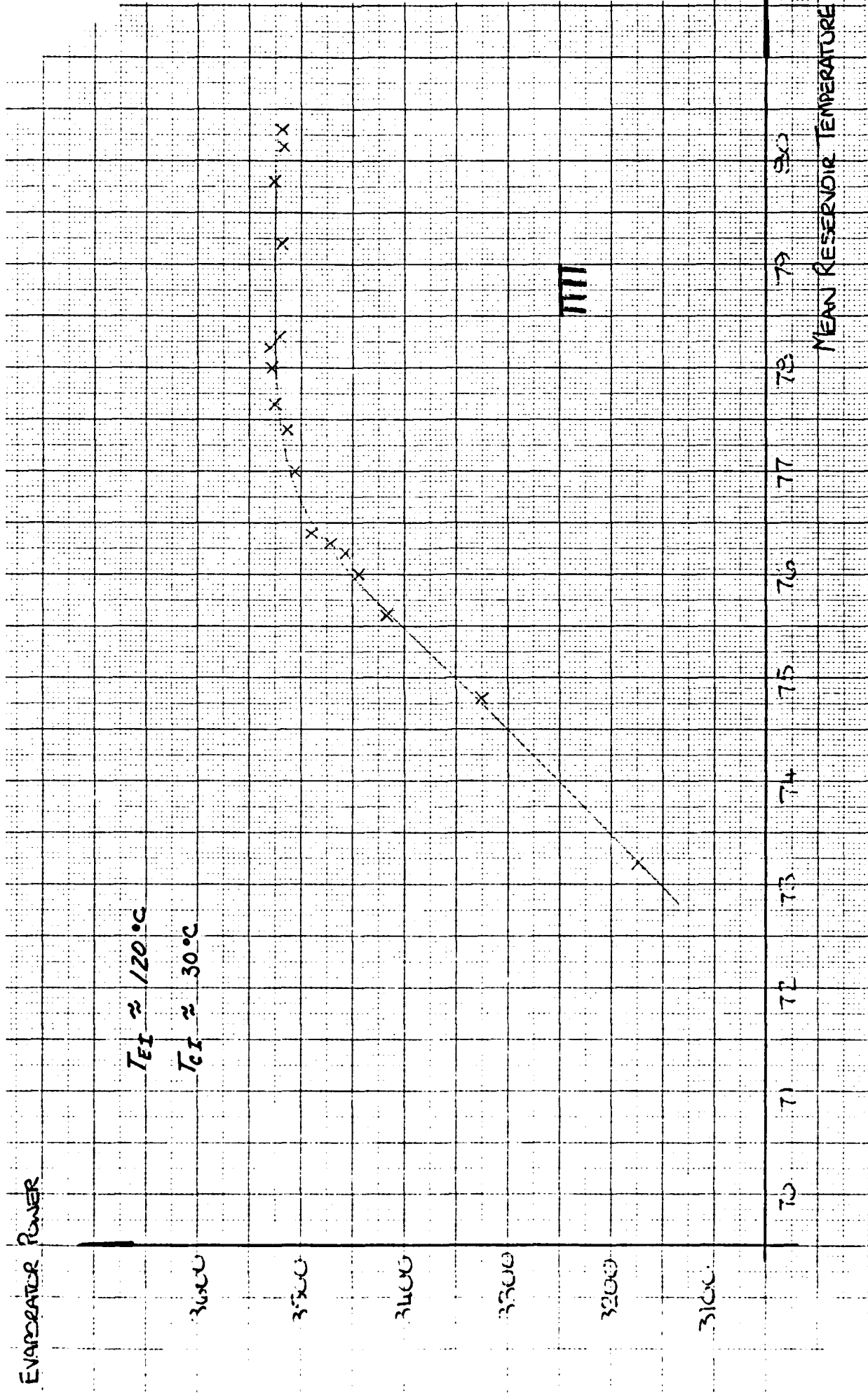
Figure 11   Upper Asymptote for The L-Prototype
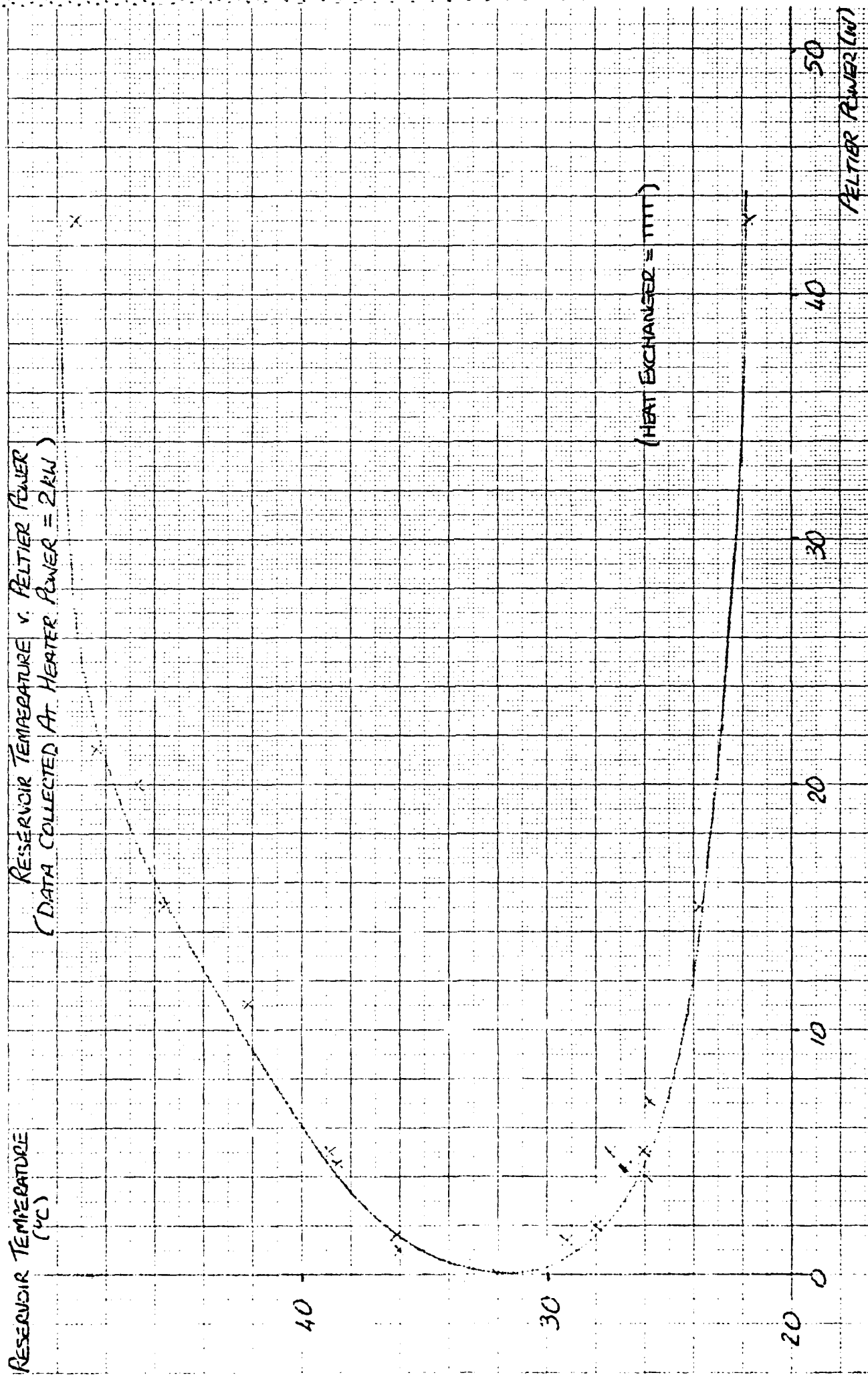
Figure 12 Teservoir Temperature vs Peltier Power For L-Prototype
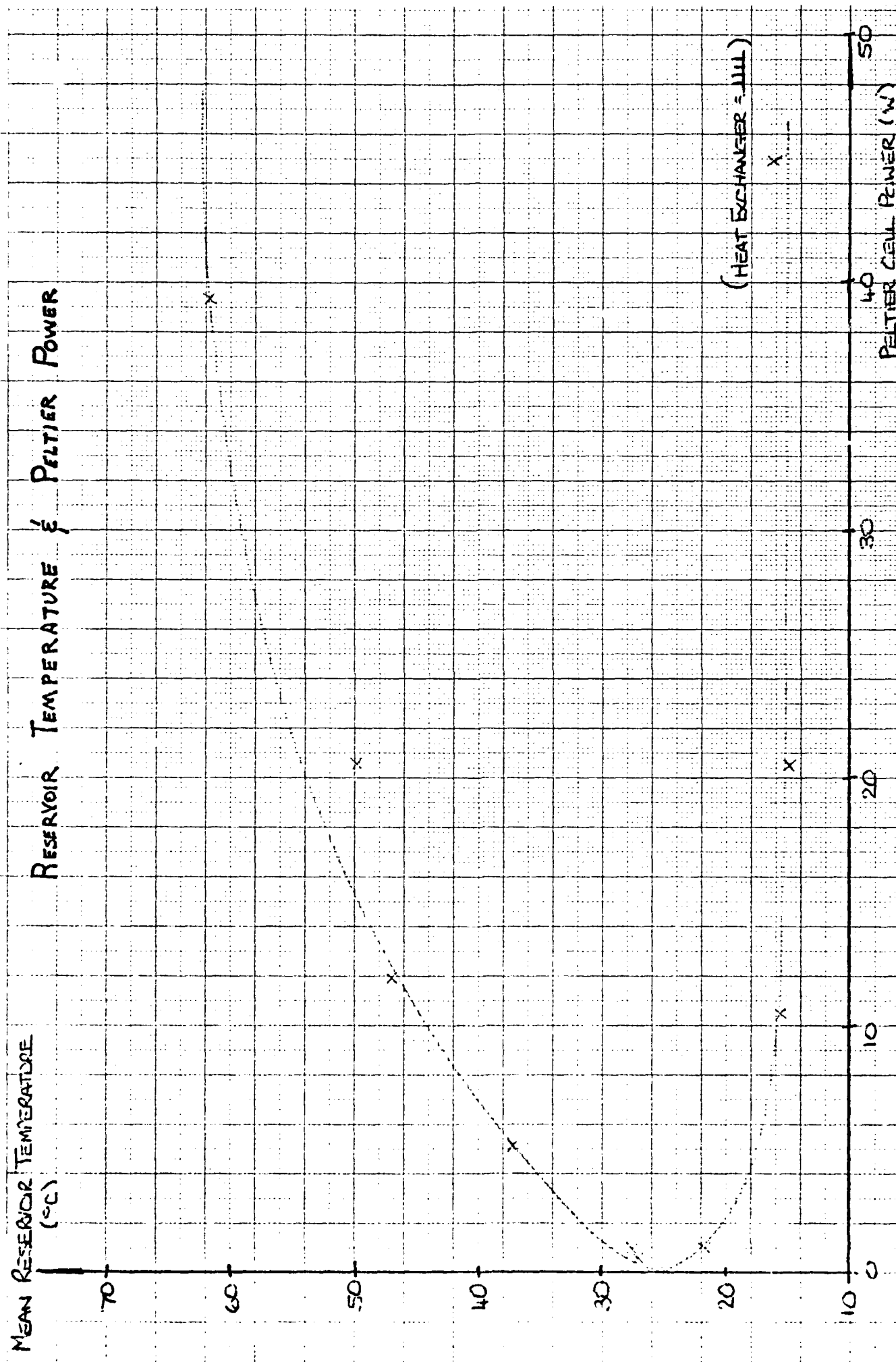
Figure 13 Reservoir Temperature vs Peltier Power For The U-Prototype
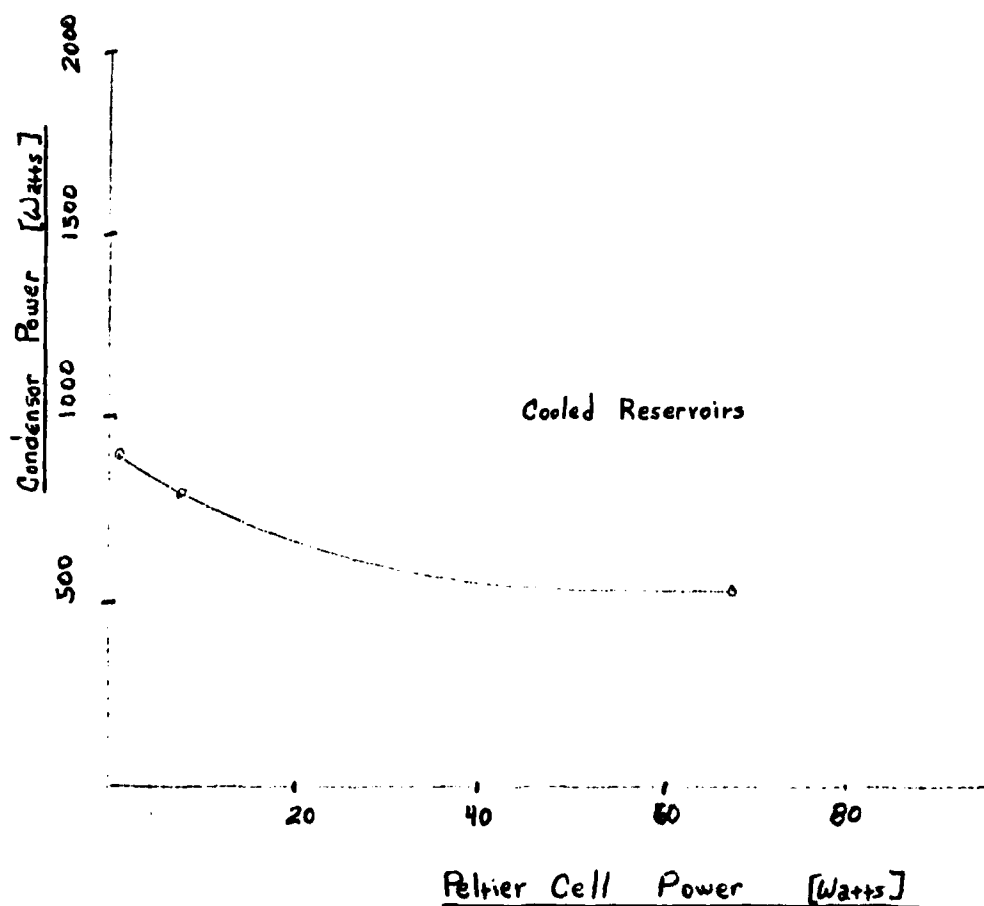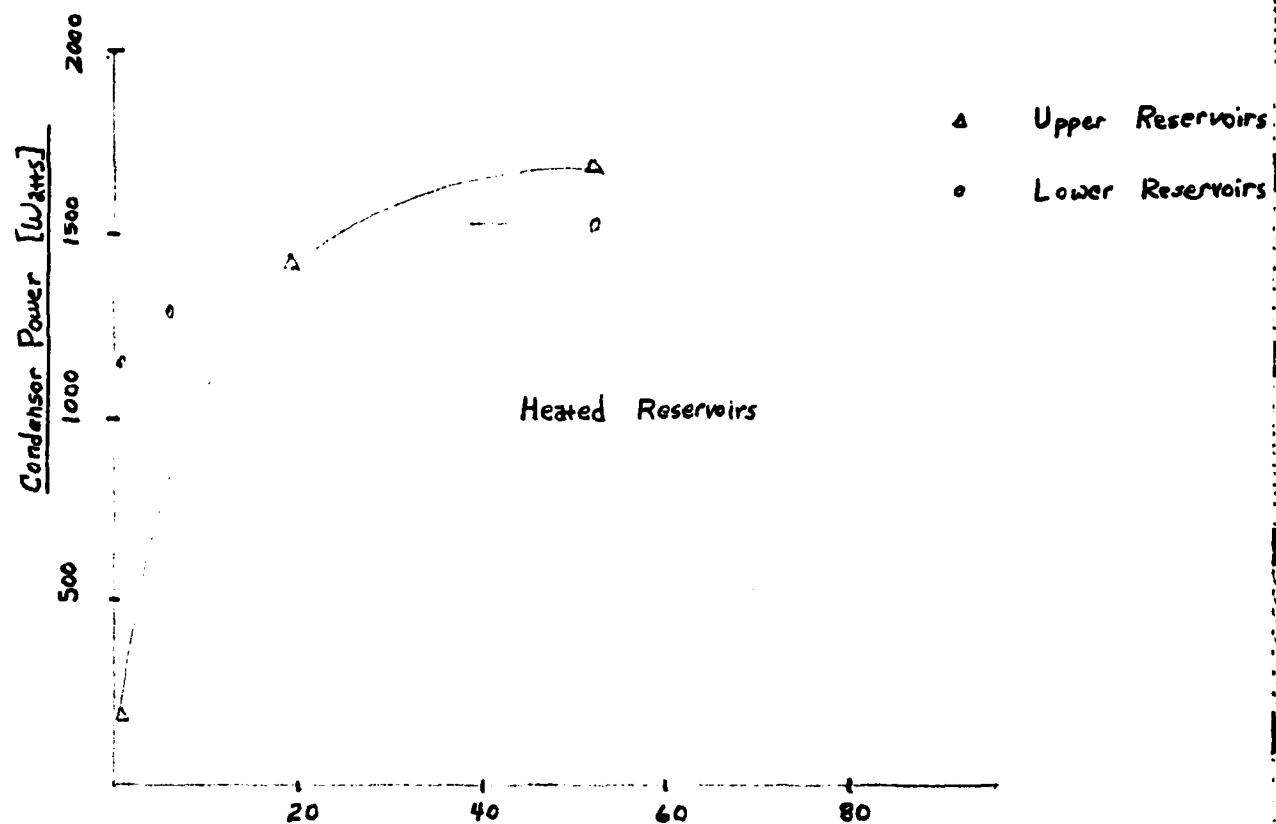
Figure 14   Condensor Power vs Peltier Power
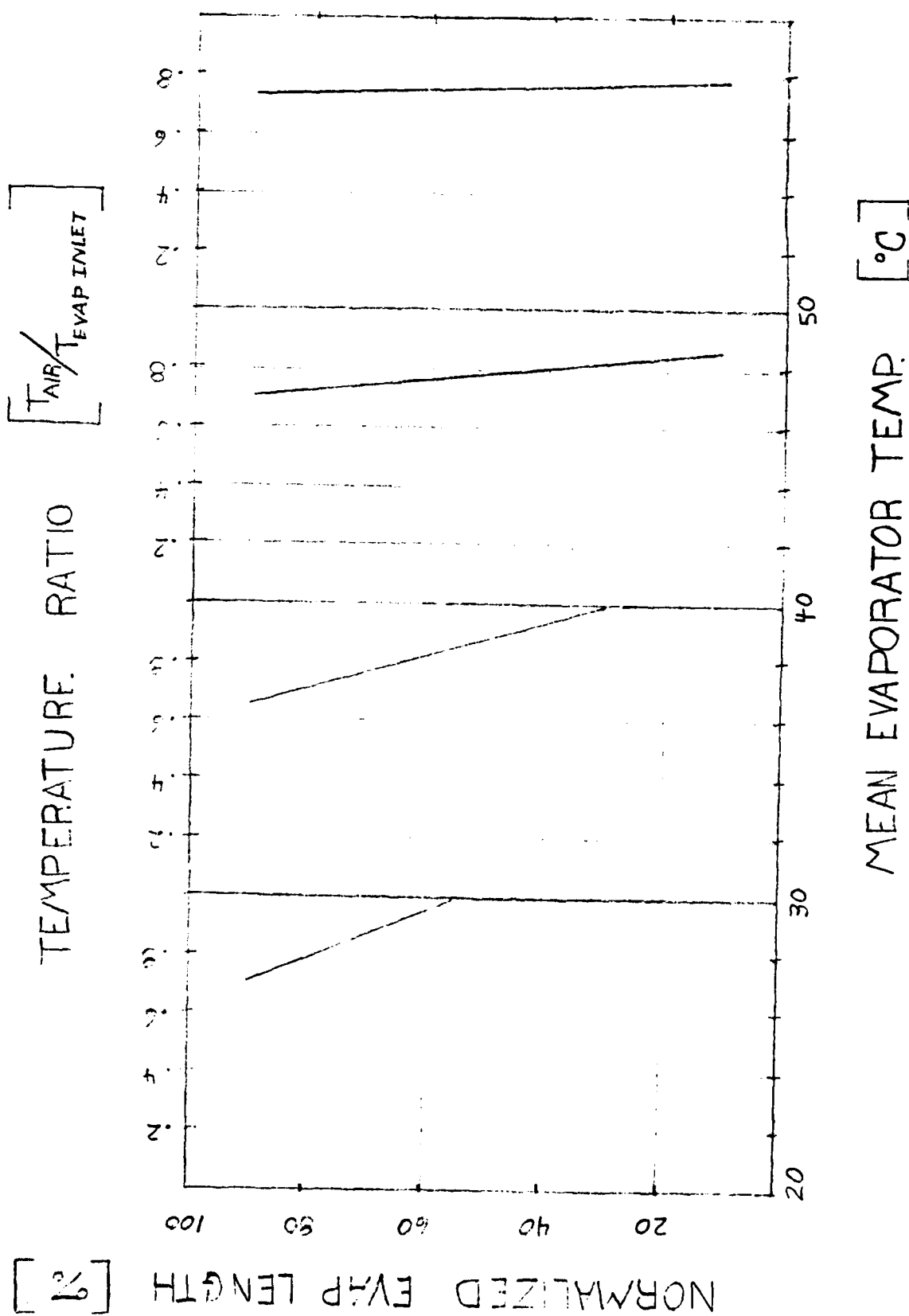
Figure 15   Reduced Evaporator Temperature
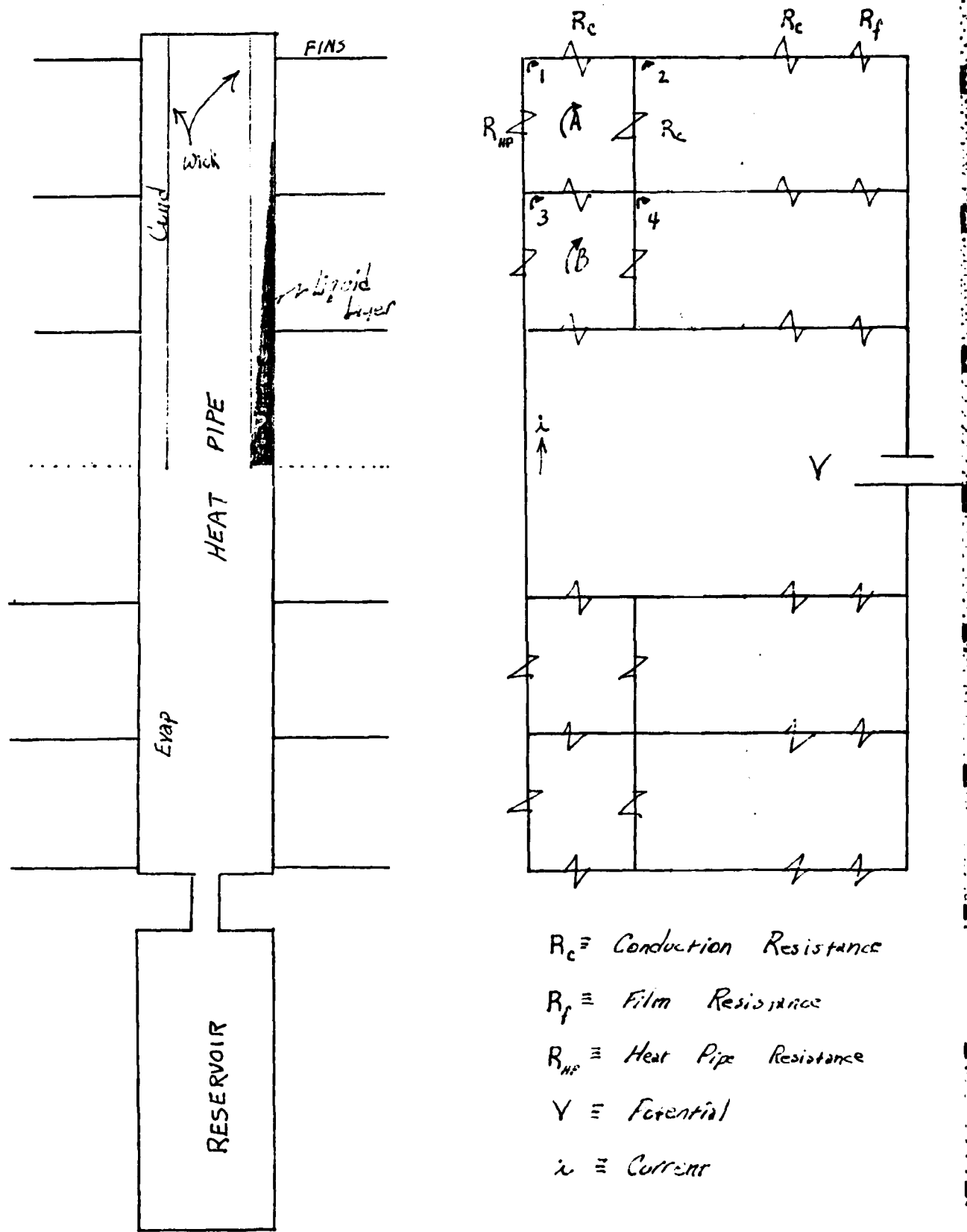
Figure 16   VCHPHX Equivalent Circuit Model

TRANSIENT RESPONSE OF HEAT EXCHANGER SUBJECT TO 20 W PELTIER CELL COOLING FROM A STEADY STATE CONDITION OF 83W HEATING

Figure 17

X = MEAN RESERVOIR TEMPERATURE
O = EVAPORATOR EFFECTIVENESS
+ = EVAPORATOR POWER

(HEAT EXCHANGER = ⊔⊔⊔)

Figure 18   Transient Response of Heat Exchanger Subject To
20 W Peltier Cell Cooling From A Steady State Condition
of 60 W Heating

X = Mean Reservoir Temperature
+ = Evaporator Power
⊙ = Evaporator Effectiveness
□ = Condenser Power
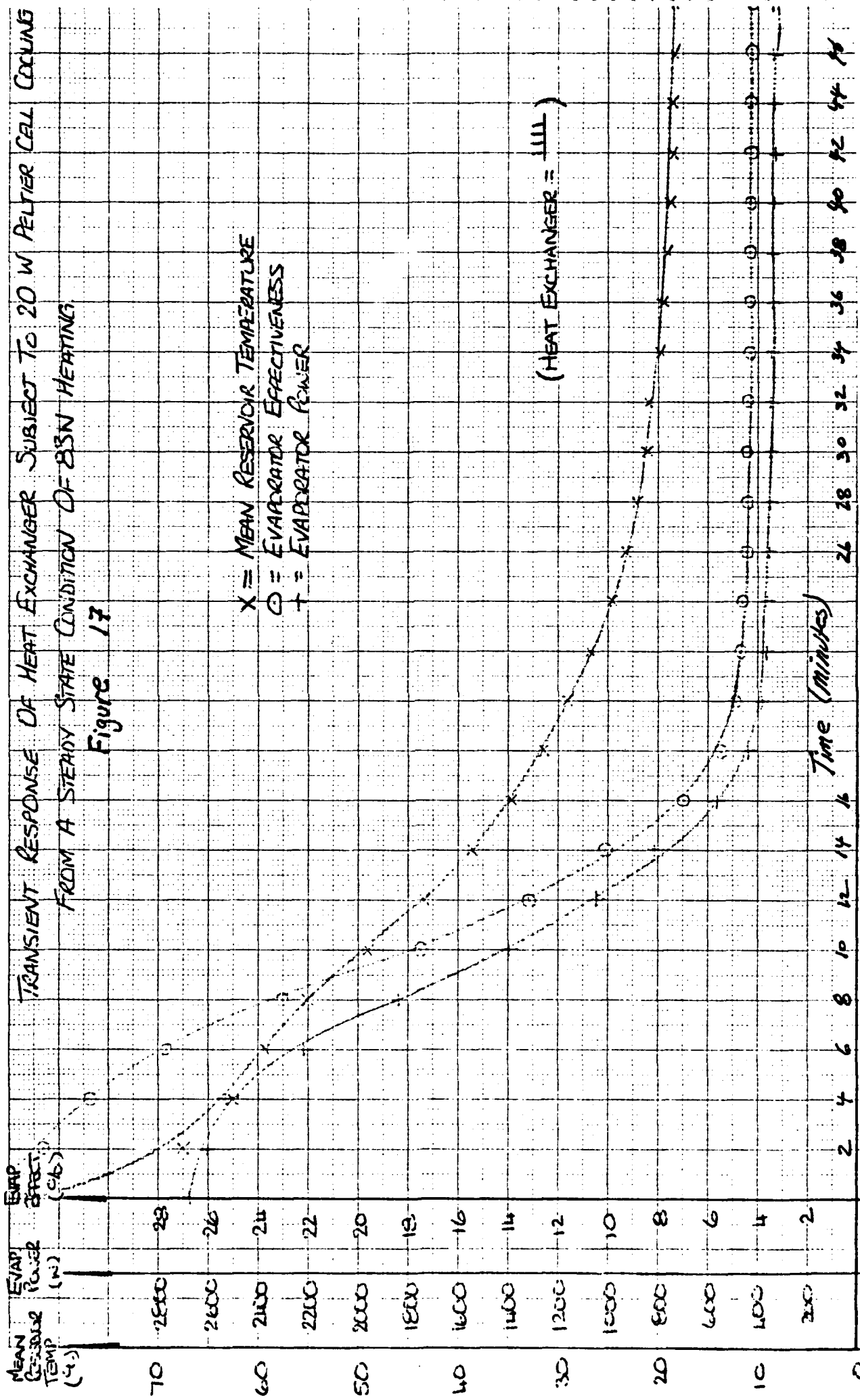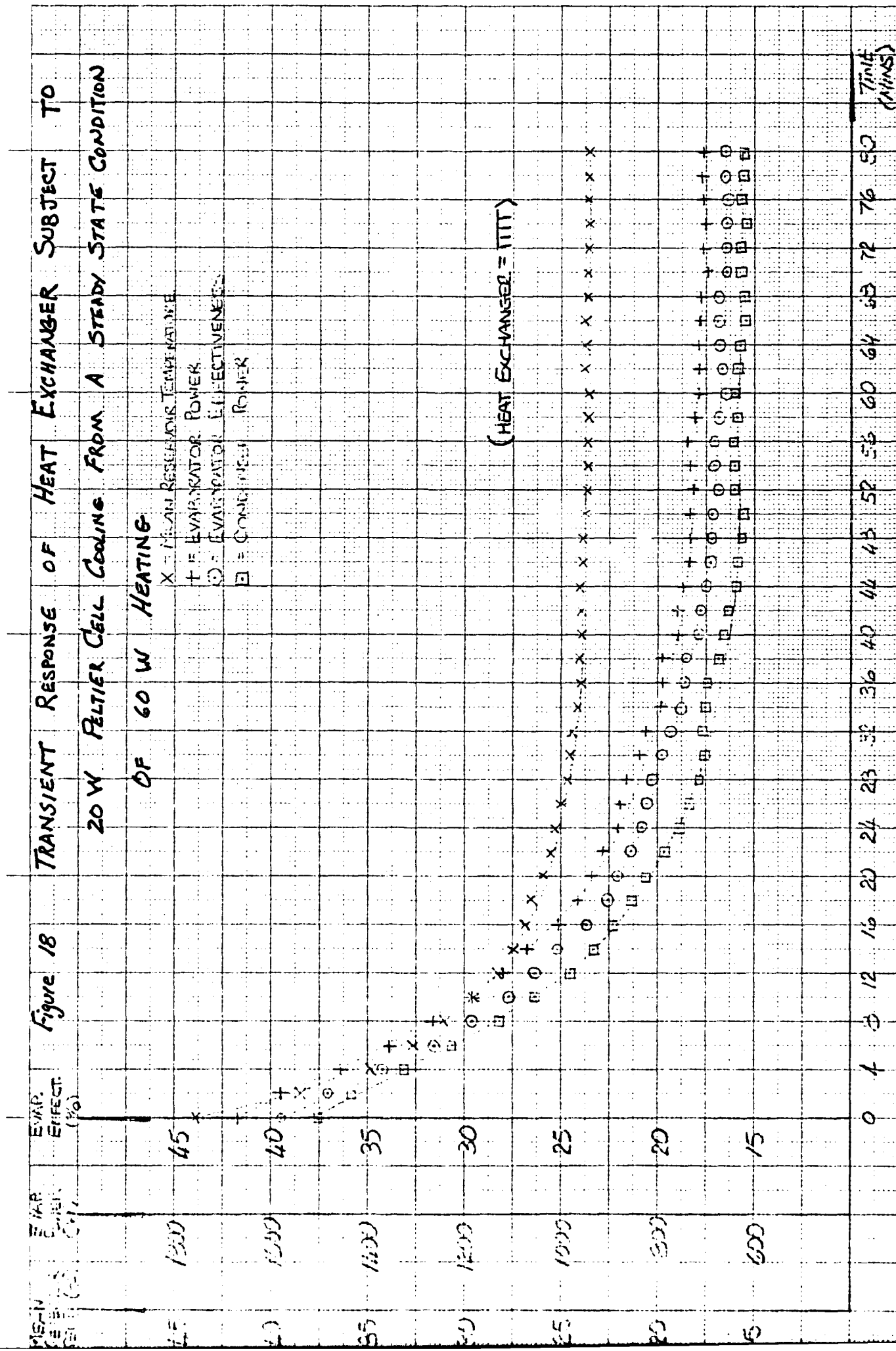
(Heat Exchanger = IIII)

Transient Response Of Heat Exchanger Subject To 8W Of Peltier Cell Heating From A Steady State Condition Of 25W Cooling

Figure 19

X = Mean Reservoir Temperature
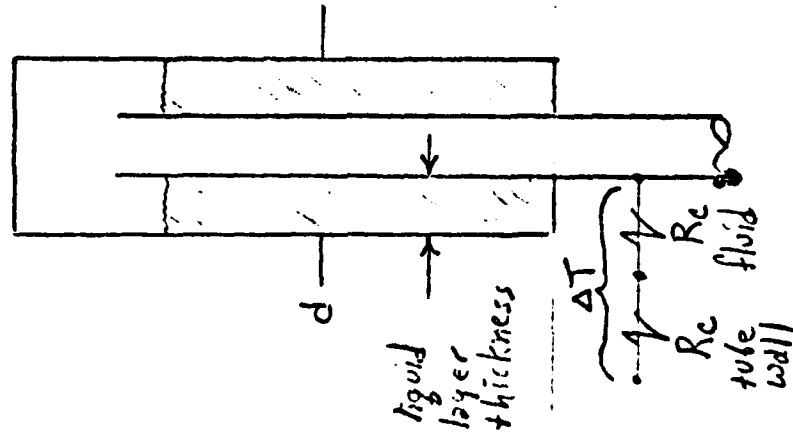⊙ = Evaporator Effectiveness
+ = Evaporator Power

(Heat Exchanger = ┴┴┴┴)

Figure 20   Construction of Liquid Reservoirs

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